A REVIEW OF HABITAT SUITABILITY CRITERIA APPLICABLE TO FOUR SALMONID SPECIES IN NEWFOUNDLAND, CANADA

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A Review of Habitat Suitability Criteria Applicable to Four Salmonid Species in Newfoundland, Canada

by

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ABSTRACT

Scruton, D. A., S. C. Riley, B. A. Bennett, F. T. Bowdring and K. D. Clarke. 2000. A Review of Habitat Suitability Criteria Applicable to Four Salmonid Species in Newfoundland, Canada. Can. Manuscr. Rep. Fish. Aquat. Sci. No. 2548: vi + 56 p + appendices.

The Canadian Department of Fisheries and Oceans (DFO) and the Department of Environment and Labour (NDOEL), in collaboration with Newfoundland and Labrador Hydro (NLH) undertook a multi-year study to investigate and develop a hierarchy of methods, from planning to project specific techniques, for prescribing instream flow needs to ensure fish habitat protection. This project included development of region specific biological criteria for use in these models/methodologies. At the outset of this project, available and published habitat criteria, both regionally and elsewhere, were reviewed to: assess regional applicability; identify approaches used in other jurisdictions; and identify appropriate methods for development of biological criteria. This report summarizes the results of this review for four salmonid species resident in insular Newfoundland; Atlantic salmon (*Salmo salar*) brook trout (*Salvelinus fontinalis*), brown trout (*Salmo trutta*) and Arctic charr (*Salvelinus alpinus*). Recommendations are made respecting the application and testing of available models/methodologies for use in insular Newfoundland including assessing spatial and temporal aspects of habitat availability in relation to fish production, validation of model assumptions, verification of model predictions, model complexity, transferability of biological criteria, and others. A number of research recommendations are also included in relation to model testing and development.

RÉSUMÉ

Scruton, D. A., S. C. Riley, B. A. Bennett, F. T. Bowdring and K. D. Clarke. 2000. A Review of Habitat Suitability Criteria Applicable to Four Salmonid Species in Newfoundland, Canada. Can. Manuscr. Rep. Fish. Aquat. Sci. No. 2548: vi + 56 p + appendices.

Le ministère des Pêches et des Océans du Canada (MPO) et le ministère de l'Environnement et du Travail de Terre-Neuve (NDOEL), en collaboration avec la société Newfoundland and Labrador Hydro (NLH), ont entrepris une étude pluriannuelle visant à élaborer une hiérarchie de méthodes, de la planification aux techniques propres au projet, visant à déterminer les besoins en matière de débit minimal aux fins de la protection de l'habitat du poisson. Ce projet comprenait l'élaboration de critères biologiques propres à la région pour ces modèles/ces méthodologies. Au début du projet, des critères disponibles et publiés concernant l'habitat, tant pour la région qu'ailleurs, ont été étudiés aux fins suivantes : évaluer leur applicabilité à la région; déterminer les approches utilisées par d'autres compétences; déterminer les méthodes appropriées d'élaboration de critères biologiques. Le présent rapport résume les

résultats de cet examen pour quatre espèces de salmonidés vivant dans la partie insulaire de Terre-Neuve : le saumon de l'Atlantique (*Salmo salar*), l'omble de fontaine (*Salvelinus fontinalis*), la truite brune (*Salmo trutta*) et l'omble chevalier (*Salvelinus alpinus*). Des recommandations sont formulées concernant l'application et la mise à l'essai de modèles/de méthodologies disponibles avec des espèces de la partie insulaire de Terre-Neuve, y compris l'évaluation des aspects spatial et temporel de la disponibilité de l'habitation relativement à la production du poisson, la validation des hypothèses des modèles, la vérification des prévisions du modèle, la complexité du modèle, la transférabilité des critères biologiques, etc. Un certain nombre de recommandations de recherche sont aussi incluses au sujet de la question de la mise à l'essai et de l'élaboration de modèles.

1.0 PREFACE

There are increasing demands on the available streamflow in Newfoundland for small and medium scale hydroelectric developments; municipal and industrial water supplies; recreational uses; pollution assimilation; and elsewhere. Reduction or regulation of flows and alteration of seasonal patterns of streamflow for such uses can have significant impacts on freshwater fish and their habitats with subsequent detrimental effects on the recreational sport fisheries which can lead to conflicting water uses. The resolution of conflicts between water users requires a variety of methodologies and management options, with varying degrees of technical complexity and sophistication, to address these issues. There are a number of qualitative and quantitative methods available to prescribe habitat flow requirements for fish. There has, however, been limited application of these techniques in Newfoundland and very little comparative evaluation of their outcomes.

The Canadian Department of Fisheries and Oceans (DFO), and the Newfoundland Department of Environment and Labour (NDEL), in collaboration with Newfoundland and Labrador Hydro (NLH) undertook a multi-year project entitled *'Evaluation of Instream Flow Needs Assessment Methodologies in Newfoundland'*. Funding for this project was provided by the Green Plan/Habitat Action Plan and the Canada-Newfoundland Agreement Respecting Water Resource Management. This project was initiated in response to the growing need for techniques and methodologies to predict and prescribe appropriate flow regimens to provide for fish habitat protection and allocation of stream flows. A three year study, initiated in June 1994, to investigate instream flow assessment methodologies was undertaken by a consortium of consultants (Jacques Whitford Environment, St. John's, NF- Acres International Ltd., St. John's, NF- Thomas R. Payne and Associates, Arcata California, USA). This study investigated a hierarchy of methods, from planning to project specific techniques, and included the Tennant Method, the Wetted Perimeter Method, and the Physical Habitat Simulation Model (PHABSIM), a tool as part of the Instream Flow Incremental Methodology.

The principle objectives of this study were: (1) to review the three main categories of methodologies available for prescribing instream flow needs for fish habitat protection; (2) to test the application of these three methodologies on three rivers on the island of Newfoundland, representative of regional hydrological regimes, fish habitat distributions, and fish species assemblages; and (3) to develop a set of criteria and guidelines for application of these methodologies, acceptable to regulatory agencies and stakeholders, for recommending flow regimens necessary to ensure management of the Province's water and fisheries resources on a sustainable basis.

In addition to this major study, additional research and investigation into development of regionally applicable instream flow needs assessment methodologies have been undertaken by the study partners outside of the scope of this project. These have included a retrospective assessment of instream flow allocations for previous projects (e.g. Scruton and LeDrew 1996, 1997), diurnal aspects related to habitat preference (LeDrew 1996,

LeDrew et al. 1996), and comparison of various habitat hydraulic models (Scruton et al. 1996, 1997a, 1998). Other studies are have been conducted to address spatial (between habitat) and temporal (seasonal) differences in habitat selection and habitat availability under winter conditions (Scruton et al. 1997b). A major component of this overall initiative has involved the development of region specific biological criteria for use in these models/methodologies. At the outset of this project, available and published habitat criteria were reviewed for applicability to Newfoundland, to identify approaches used in other jurisdictions, and to identify appropriate methods for development of biological criteria. This report summarizes the results of this review for four salmonid species resident in Newfoundland; Atlantic salmon *(Salmo salar),* brook trout *(Salvelinus fontinalis),* brown trout *(Salmo salar)* and arctic charr *(Salvelinus alpinus).*

2.0 INTRODUCTION

Micro- and macro- habitat selection by salmonids in riverine environments are important considerations in assessing productive capacity of habitats, effect of flow variability on habitat quantity and quality, and ultimately in assessing effects of resource developments that strive to utilize or control streamflows. Within a range of habitat available to stream dwelling salmonids there is a narrower range of conditions that fish species select as the preferred range for that habitat variable. Frequently, the association of fish with their habitats reflecting preference is structured into habitat criteria (indices) for use in models to predict changes in habitat availability and suitability in relation to changes in the biotic or abiotic environment.

Habitat models such as the Instream Flow Incremental Methodology (IFIM) and Habitat Suitability Indices (HSI's) have enjoyed widespread use throughout North America and elsewhere and could serve as valuable tools in the assessment of the potential environmental impacts of various types of development in Newfoundland rivers. The application of such models, however, requires detailed information about the habitat use of salmonids in Newfoundland. This document is therefor intended to review habitat use and suitability information, both regionally and elsewhere, for four salmonid species that are found on the island of Newfoundland (Atlantic salmon; brook trout; brown trout; Arctic char). The objectives of this review were to: (i) compile and assimilate available habitat use and suitability information for the four salmonids in insular Newfoundland from regional studies and elsewhere; (ii) assess the utility of this information for use in habitat and environmental assessment in Newfoundland given regional geomorhphological conditions and fish communities, (iii) identify generic and region specific knowledge gaps, (iv) and determine the appropriate approach(es) for developing regionally applicable biological/habitat criteria for salmonid fishes. This review was the initial step in a larger study to assess and develop instream flow needs assessment methodologies. As part of this larger study, there have been a number of initiatives to develop region and river specific habitat suitability and preference criteria. The results of these studies are not included in this review and are presented/published elsewhere.

3.0 HABITAT USE

3.1 Atlantic Salmon

The Atlantic salmon is native to streams throughout the North Atlantic basin in Europe and North America (Scott and Crossman 1973). Most Atlantic salmon stocks are anadromous, but freshwater populations, known in eastern North America as ouananiche, also occur throughout the range of the species. The morphology and behaviour of the two forms are similar (Riley *et al.* 1989; Sayers 1990), but the vast majority of research has been conducted on the anadromous form. A fairly comprehensive review of landlocked salmon was reported for Maine by Havey and Warner (1970). Unfortunately, that work has not been expanded or updated in the intervening decades.

3.1.1 Spawning, Incubation and Emergence

Atlantic salmon ascend rivers to spawn in autumn. In Newfoundland, on average, spawning occurs during the first two weeks of November (Scruton 1986). Females prepare a redd, usually at the tail of a pool, where eggs are deposited and fertilized by a male or males (since precocious males may also be present) (Jones 1959; Jordan 1981). The female then covers the eggs with gravel excavated from upstream. The age at maturity of Atlantic salmon varies widely depending on environmental variables (Schaffer and Elson 1975; Power 1981). Some male parr also mature and take part in spawning (Jones 1959; Dalley *et al.* 1983; Myers 1984; Prévost *et al.* 1992).

Atlantic salmon spawn at water temperatures between 3 and 11°C, but usually below 7°C (DeCola 1970; Peterson *et al.* 1977; Jordan 1981). This species requires dissolved oxygen (DO) concentrations of at least 6 $mg \cdot L^{-1}$ for successful reproduction (DeCola 1970; Elson 1975). Reproduction will fail at pH levels less than 5.0 (Haines 1981).

The water depth at spawning sites ranges from 0.2-0.7 m (Jones 1959; Pratt 1968; Peterson 1978; Beland *et al.* 1982; deGraaf and Chaput 1984; Heggberget *et al.* 1988). Water velocity at spawning sites is also quite variable, ranging from 0-0.8 $m \cdot s^{-1}$ (Elson 1975; Beland *et al.* 1982; deGraaf and Chaput 1984; Heggberget *et al.* 1988); although, there is some evidence that salmon will not spawn in velocities of less than about 0.1 $m \cdot s^{-1}$ (Jones 1959; Crisp and Carling 1989). The physical characteristics of spawning areas may vary greatly between different rivers in the same geographic area (deGraaf and Chaput 1984). Streambed substrates at spawning sites are usually 40-50% gravel or larger particles (Warner 1963; Peterson 1978). Heggberget *et al.* (1988) report mean diameters of surface particles on salmon redds to be 7.8-12.5 cm. Ouananiche spawning has been documented in substrates containing up to 18% fines (sand, silt and clay) with little apparent effect on survival (Havey and Warner 1970).

Eggs remain in the gravel until the following spring. In insular Newfoundland, the incubation period is approximately 4-5 months (Scruton 1986). The incubation period is

a function of temperature (Leim and Scott 1966; Jordan 1981; Danie *et al.* 1984; Scruton 1986). Alevins remain in the substrate for a period after hatching, begin feeding while still in the substrate, and emerge (as fry) from the gravel at night (Gustafson-Marjanen 1982; Gustafson-Marjanen and Dowse 1983). Fry emerge from April to June, depending on the geographic location (Egglishaw and Shackley 1977; Jordan 1981; Randall 1982). The time of initial feeding is dependent on temperature and flow regime (Jensen *et al.* 1991).

Egg-to-fry survival is quite variable, and may be influenced by substrate characteristics (Peterson and Metcalfe 1981) and environmental variables such as winter temperatures and water levels (Chadwick 1982). The optimal temperature for incubation is 6°C, but temperatures between 0.5-9°C are adequate (DeCola 1970; Peterson *et al.* 1977).

3.1.2 Juveniles

Fry begin to disperse and establish territories immediately after emergence from the redd (Allen 1940b; Kalleberg 1958; Randall 1982), and will feed on whatever suitable sized prey is most abundant at the time (Williams 1981). This is a period of high mortality (Ottaway and Clarke 1981). Optimal growth of juveniles occurs at 15 to 19°C (DeCola 1970; Morrison 1989), with little growth occurring below 7°C (Symons 1979). It has been suggested that salmon populations are limited to rivers with a minimum of 100 days above 6°C (Power 1969), but in some cold Norwegian rivers this may not apply (Jensen and Johnsen 1986). The laboratory-measured lethal pH for juveniles is 4.0 (Daye and Garside 1977), but evidence from the field suggests that mortality can occur at pH below 5.0 (LaCroix 1989).

The habitat use of juvenile Atlantic salmon has been the subject of a great deal of research (reviewed by Heggenes 1990; Gibson 1993). Habitat use varies with fish size (Kennedy and Strange 1982; DeGraaf and Bain 1986; Heggenes 1990), so it is useful to classify juveniles as fry (< 40 mm), small parr (40-70 mm), and large parr (>70 mm), although not all studies make such a distinction and this is by no means a standard classification system (cf. Heggenes 1990).

Juvenile Atlantic salmon habitat use may be affected by a number of factors, including water temperature (Gibson 1978), season (Rimmer *et al.* 1983; Cunjak 1988), discharge (Heggenes and Saltveit 1990), fish size (MacCrimmon 1954; Symons and Heland 1978; Kennedy and Strange 1982), and predation risk (Huntingford *et al.* 1988; Gotceitas and Godin 1993). The habitat use of salmon parr also depends strongly on interactions with other fishes, especially brown trout (Kalleberg 1958; Gibson and Cunjak 1986; Kennedy and Strange 1986) and brook trout (Gibson 1973; Gibson and Power 1975; Chiasson *et al.* 1990; Gibson *et al.* 1993). Moreover, different methods of collecting habitat use data are biased in different ways (Heggenes *et al.* 1991). It is therefore, difficult to generalize about parr habitat use.

3.1.3 Habitat Variables

(1) Water Velocity

It is suggested that water velocity is the primary variable determining habitat selection by Atlantic salmon in North American rivers (deGraaf and Bain 1986). Young-of-the-year Atlantic salmon (i.e., fry) have been reported to occupy stream areas with relatively low water velocities (< 40 $cm \cdot s^{-1}$: Elson 1967; Knight *et al.* 1981; Rimmer *et al.* 1984; Trial and Stanley 1984; DeGraaf and Bain 1986; Morantz *et al.* 1987), although fry were observed in much faster water (50-65 $cm \cdot s^{-1}$) by Symons and Heland (1978). Of the studies which suggested that fry occupied lower water velocities, the mean velocities where fry were found ranged from 5 $cm \cdot s^{-1}$ (Trial and Stanley 1984) to 32 $cm \cdot s^{-1}$ (Morantz *et al.* 1987). In developing habitat suitability curves in Newfoundland rivers, Scruton and Gibson (1993) found that optimum fry suitability ranged from 20 $cm \cdot s^{-1}$ to 60 $cm \cdot s^{-1}$. Some studies suggest that larger parr occupy faster water than fry (MacCrimmon 1954; Keenleyside 1962; Wankowski and Thorpe 1979; Rimmer *et al.* 1984), others find the opposite (Saunders and Gee 1964; Elson 1967; Chadwick and Green 1985; Morantz *et al.* 1987; Cunjak *et al.* 1989; Heggenes and Saltveit 1990), and Trial and Stanley (1984) observe both phenomena in different rivers. Scruton and Gibson (1993) found that the optimum suitability for parr in Newfoundland rivers ranged from 10 $cm \cdot s^{-1}$ to 50 $cm \cdot s^{-1}$. Larger parr appear to use a wider variety of velocities than smaller parr (Saunders and Gee 1964; Gibson and Coté 1982; Chadwick and Green 1985). Young Atlantic salmon in Norway appear to prefer mean water velocities between 10-50 $cm \cdot s^{-1}$ and avoided velocities >60 $cm \cdot s^{-1}$ (Heggenes and Saltveit 1990). The wide variation and lack of agreement among these studies may be due to a number of things, including differences in the way that velocities are measured or reported, the effects of other fish species on habitat use, and differences in habitat availability among sites. In general, parr tend to use areas with velocities ranging from 5-100 $cm \cdot s^{-1}$ (Heggenes 1990). Atlantic salmon parr are less buoyant than other salmonids, and tend to remain on the substrate, which may allow them to occupy faster water (Saunders 1965; Sosiak 1982). In winter, parr move into areas with very slow water velocities, often hiding beneath large substrate particles (Rimmer *et al.* 1983; Cunjak 1988).

The water velocity measured at the anterior end of an undisturbed fish ("focal point velocity", "snout velocity" or "nose velocity") has been identified as the most consistent characteristic of the habitat used by juvenile Atlantic salmon in streams (Heggenes 1990). During summer, juvenile Atlantic salmon select feeding sites with nose velocities ranging from 5-25 $cm \cdot s^{-1}$ (DeGraaf and Bain 1989; Morantz *et al.* 1987; Heggenes 1990: but see Shustov *et al.* 1981; Rimmer *et al.* 1984; Heggenes and Saltveit 1990). Salmon parr appear to select relatively similar water velocities for holding stations in a variety of different rivers throughout the range of the species, and this may be the reason that they have been observed to use a wide range of depths and substrates (see below).

(2) Water Depth

Many early studies reported that the density of parr was variable within a river system, with

higher parr densities usually being found in riffles (Keenleyside 1962; Saunders and Gee 1964; Maitland 1965; Elson 1975; Jones 1975). Other studies found that parr tended to occupy deeper water in large rivers, while sympatric brown trout were found in shallower areas (Lindroth 1955; Elson 1967; Symons and Heland 1978; Heggberget 1984). As noted by Heggenes (1990), this pattern appears to be reversed in smaller streams, where brown trout occupy deeper areas than parr (Baglinière and Champigneulle 1982; Kennedy and Strange 1982; Egglishaw and Shackley 1985; Gibson and Cunjak 1986).

Young-of-the-year Atlantic salmon tend to occupy shallow areas, often near stream margins (MacCrimmon 1954; Elson 1967; Symons and Heland 1978; Kennedy and Strange 1982, 1986; Gardiner 1984), but this varies from stream to stream and fry may occur in water up to 1 m deep (Francis 1980; Knight *et al.* 1981; Baglinière and Champigneulle 1982; Rimmer *et al.* 1984; Trial and Stanley 1984; DeGraaf and Bain 1986; Morantz *et al.* 1987). In general, however, fry are often found in shallower water than older parr (Symons and Heland 1978; Egglishaw and Shackley 1982; Kennedy and Strange 1982, 1986); the wide range of depths observed to be occupied by fry in different studies precludes a more precise generalization (see Heggenes 1990).

For fry and parr in Newfoundland rivers, optimum suitability ranges from 15 to 20 cm (fry) and from 15 to 25 cm (parr). In shallower waters (< 10 cm), fry and parr were less plentiful (Scruton and Gibson 1993).

(3) Substrate

Because the estimation of substrate size can be subjective and is often difficult, this is probably the least reliable habitat variable. Further fish may be selecting the micro velocity associated with the size and shape of the substrate particle. Juvenile salmon occupy areas with a wide range of substrate types, but seem to prefer larger substrate particles (Heggenes 1991). Larger parr appear to prefer larger substrate particles (cobble-boulder) than smaller parr (pebble) and fry (Symons and Heland 1978; Baglinière and Champigneulle 1982; Rimmer *et al.* 1984; DeGraaf and Bain 1986; Morantz *et al.* 1987). In rivers in insular Newfoundland, fry are most abundant over pebble/cobble dominated substrate, whereas parr show a preference for boulder dominated substrates (Scruton and Gibson 1993). Parr choose larger substrate particles in winter, when they often remain beneath the substrate (Gibson 1978; Rimmer *et al.* 1983; Hearn and Kynard 1986; Cunjak 1988). The importance of substrate as a habitat variable may depend on the general habitat type (e.g., riffle vs. run: deGraaf and Bain 1986).

(4) Cover

Since Atlantic salmon parr often shelter in the substrate (MacCrimmon 1954; Rimmer *et al.* 1983; Cunjak 1988), their use of overhead cover may be relatively less than other salmonid species (e.g., Heggenes 1991). There is evidence, however, that parr use overhead cover (Pickering *et al.* 1987; Heggenes and Traaen 1988). In Newfoundland streams, parr showed a wide range of suitability preference for overhead cover (Scruton and Gibson 1993). Parr have been shown to prefer shade in shallow water, but to prefer

deeper water if given the choice (Gibson 1978). Atlantic salmon parr were more likely to occupy shallow water devoid of cover than were rainbow trout in Vermont streams (Hearn and Kynard 1986). Cover, like substrate, is a difficult variable to quantify (Orth 1983; Heggenes 1988d).

Optimum suitability for instream cover for Newfoundland Atlantic salmon fry appears to be in the range of 0 to 10%. Suitability curves for parr show a wide range in optimum suitabilities, with a marked decline in suitability above 80% cover.

(5) Temperature

Moreau and Moring (1993) observed that in Maine critical water temperature appears to be 28°C. At this temperature, salmon moved to cooler waters. Other habitat characteristics were disregarded when water temperatures reached this level. Havey and Warner (1970) reported 24°C as the maximum tolerated by landlocked salmon. Movement patterns of young salmon in autumn appears to be associated with declines in water temperature below 7°C (Hesthagen 1988). Jensen *et al.* (1989) note that the lower limit for growth of Atlantic salmon in Norway is approximately 7°C. At temperatures below 8°C, experiments show that salmon required more time to reach the stage of initial feeding than at temperatures above 8°C (Jensen *et al.* 1989); additionally, at temperatures below 7°C, salmon move from riffles to pools and reduce or stop feeding. The most complete laboratory study of the thermal performance is that of Elliot (1991).

(6) Atypical Habitat Use of Atlantic Salmon Parr

The majority of salmon parr that have been studied have occupied shallow stream reaches with relatively fast water velocities and large substrate (Keenleyside 1962; Elson 1967; Symons 1976; Symons and Heland 1978; Wankowski and Thorpe 1979; Rimmer *et al.* 1983, 1984; DeGraaf and Bain 1986; Morantz *et al.* 1987; Heggenes 1990), and have generally not been observed outside of these "typical" habitats. In other studies, however, parr have been observed to use deeper, slower areas of rivers (Gibson and Coté 1982), pools (Allen 1940a; Saunders and Gee 1964), and estuaries (Cunjak *et al.* 1989, Cunjak 1992). Several authors have also noted the presence of Atlantic salmon parr and fry in lakes (Pepper 1976; Chadwick and Green 1985; Pepper *et al.* 1985; Ryan 1986; Einarsson *et al.* 1990). There is some evidence that parr migrate to lakes in autumn (Einarsson *et al.* 1990), but other studies indicate that parr undergo limited seasonal movements (Saunders and Gee 1964; Rimmer *et al.* 1983; deLeaniz 1989; but see Cunjak and Randall 1993). The use of lakes by parr is very common in Newfoundland (Pepper 1976; Hutchings 1986; O'Connell and Ash 1989; Ryan 1993), suggesting that some factor affecting habitat use is different here than in the majority of the range of the species, where "typical" habitat use is the norm. It has been suggested that the relative lack of fish predators or competing species in Newfoundland may allow parr to exploit habitats otherwise unavailable to them, including lakes (deGraaf and Chaput 1984; O'Connell and Ash 1993). This idea is not supported by the work of Heggenes (1991), who found little evidence of a habitat shift in parr in the absence of competitors. The suitability of lakes as parr habitat in other areas supporting depauperate fish faunas has, however, been noted

(Rimmer and Power 1978; Einarsson *et al.* 1990). Habitat use information from other areas should be very cautiously applied to Newfoundland rivers until more research is conducted on potential reasons for the atypical habitat use of parr in Newfoundland.

3.2 Brook Trout

The brook trout is native to the eastern half of North America from northeastern Georgia to the Ungava peninsula of northern Labrador, and has been widely introduced outside of its native range (MacCrimmon and Campbell 1969). The native range of brook trout, however, is being reduced due to the encroachment of exotic salmonid species such as brown trout and rainbow trout (Waters 1983; Larson and Moore 1985) and the effects of acid precipitation (Simonin *et al.* 1993). The brook trout is one of the most abundant freshwater fish in insular Newfoundland (Scott and Crossman 1964). Brook trout show great diversity in age at maturity and maximum size, ranging from stunted populations which mature at a few inches long (Power 1980) to populations with individuals reaching weights of over 5 kg (Flick 1977). Some populations are anadromous (White 1940; Smith and Saunders 1958), but the majority are not (Scott and Crossman 1973).

3.2.1 Spawning, Incubation and Emergence

The spawning characteristics, apart from the migration to and from the sea, of both the anadromous and non-anadromous (commonly referred to as mud trout) populations of the brook trout are similar (Scott and Crossman 1964). Brook trout spawn in the fall, usually in areas of upwelling groundwater (Hazzard 1932; Benson 1953; Webster and Eiridsdottier 1976), including lentic areas (Fraser 1985; Cowan and Baggs 1988). Upwelling water is not necessary for spawning, but appears to improve egg survival (Hale and Hilden 1969). Spawning behaviour of brook trout generally occurs at temperatures between 4-10°C and has been well-described (Greeley 1932; Hazzard 1932; Smith 1941; Needham 1961; Power 1980). In Newfoundland, spawning was observed to have occurred at temperatures ranging from 3.5-9°C (Scott and Crossman 1964). Scruton (1986) reports that spawning occurs when temperatures are between 4.4-9.4°C. Although the presence of upwelling water is more important than substrate size for successful spawning, large amounts of fine sediment in the substrate can reduce spawning success (Saunders and Smith 1965; Burns 1970; Witzel and MacCrimmon 1982; Alexander and Hansen 1986). Brook trout remove fine sediment from the substrate during spawning (Young *et al.* 1989). Optimum temperatures for egg incubation are 4.5-11.5°C (MacCrimmon and Campbell 1969). At pH levels below 4.5-5.5, egg survival decreases (Kwain and Rose 1985; Cleveland *et al.* 1986; Ingersoll *et al.* 1990), and acidification effects on survival may be more important than the physical characteristics of redds (Fiss and Carline 1993). The level of sensitivity to pH toxicity decreases as brook trout get older (Ingersoll *et al.* 1990).

Eggs remain in the gravel until the yolk sac is absorbed, at which time (late spring, exact timing depending on temperature) the alevins emerge and begin to feed on invertebrates (Williams 1981). Mortality related to low pH may be most common immediately after

hatching (Fiss and Carline 1993). The optimum temperature range for brook trout fry is 8-15.4°C (McCormick *et al.* 1972; Peterson *et al.* 1979), with an upper limit of about 22-24°C (MacCrimmon and Campbell 1969; Barton *et al.* 1985; Meisner 1990a). Alevins tend to seek cover and are usually found in water of low velocity (8-20 $cm \cdot s^{-1}$) and moderate depth (25-50 cm: Griffith 1972; Williams 1981). Growth of fry in lacustrine areas appears to be similar to that in streams (Curry *et al.* 1993).

3.2.2 Juveniles and Adults

Unlike Atlantic salmon, for which a "typical" habitat (riffles) is recognized, brook trout have very generalized habitat requirements. Brook trout are found in tiny streams, ponds, lakes and large rivers (Behnke 1980; Power 1980). Ryan and Knoechel (1994) observed that in insular Newfoundland the movement of brook trout towards the lakes or ponds is greatest at ages 1 and 2. Water temperature is an important factor in limiting brook trout populations (Creaser 1930; McCormick *et al.* 1972; Bowlby and Roff 1986; Meisner 1990b), although pH and groundwater inflow have also been identified as important habitat variables (Schofield 1990; Beauchamp *et al.* 1992). The southern limit of brook trout distribution in North America corresponds with the 15°C groundwater isotherm (Meisner 1990b). The temperature limits for brook trout range from about 0-25°C (Embody 1921; MacCrimmon and Campbell 1969; Hynes 1970; Jirka and Homa 1990), while the optimum range is 10-19°C (Hoover 1939; Baldwin 1951; Cooper 1953; Mullan 1958; Hokanson *et al.* 1973). Brook trout require oxygen concentrations near saturation and pH levels above 4.5-5 (Power 1980). Brook trout production is usually greater in watersheds with high alkalinity and conductivity (Cooper and Scherer 1967; Donald *et al.* 1980). The movement and spatial distribution, and therefore habitat use, of brook trout may vary among different populations (Van Offelen *et al.* 1993). In two ponds in Newfoundland, brook trout were more abundant in the benthic regions (O'Connell *et al.* 1990).

3.2.3 Habitat Variables

(1) Water Velocity

The range of water velocities suitable for juvenile brook trout has been identified as 0-45 $cm \cdot s^{-1}$, with an optimum range of 6-21 $cm \cdot s^{-1}$ (Jirka and Homa 1990), although many trout may occupy the slowest water available (Wickman 1967; Wesche 1974) and are capable of holding in water as fast as 150 $cm \cdot s^{-1}$ (Jirka and Homa 1990). Fausch and White (1981) observed trout occupying resting positions with mean focal point velocities of 12-13 $cm \cdot s^{-1}$ in allopathy and 19-20 $cm \cdot s^{-1}$ in sympatry with brown trout, while the allopatric and sympatric feeding position mean velocities were greater (18-25 and 21-27 $cm \cdot s^{-1}$, respectively). Griffith (1972) observed brook trout using mean focal point velocities of 8-11 $cm \cdot s^{-1}$, with little or no difference between allopatric trout and those sympatric with cutthroat trout. He also found little difference in focal point velocity among age-classes of trout. Cunjak and Power (1986) observed brook trout occupying positions with mean focal points of 3-15 $cm \cdot s^{-1}$ in summer.

Brook trout appear to use positions in slower water in winter (Cunjak and Power 1986; Chisolm *et al.* 1987). Cunjak and Power (1986) found that brook trout used positions with mean focal points of 3-18 $cm \cdot s^{-1}$ in winter (range 1.5-23 $cm \cdot s^{-1}$), and they also noted that young-of-the-year tended to occupy positions in slower water than older fish. Brook trout also tended to aggregate in winter in an Ontario stream (Cunjak and Power 1986).

(2) Water Depth

Brook trout are generally found in water ranging from 6-90 cm deep, with the optimum range being approximately 18-40 cm (Jirka and Homa 1990). Cunjak and Power (1986) found brook trout to have mean focal point depths of 32-92 cm in summer and 28-95 cm in winter. Chisholm *et al.* (1987) found the majority of trout occupying depths of less than 60 cm in winter. Most of the trout observed by Griffith (1972) occupied positions in 40-70 cm of water.

(3) Substrate

Relatively less attention has been given to the substrates used by brook trout. Fluvial brook trout occupy a wide range of substrates, but are generally associated with clean substrates ranging from gravel to boulder (Keenleyside 1962; Joy *et al.* 1981; Nestler *et al.* 1985; Chisholm *et al.* 1987; Jirka and Homa 1990). Juvenile and adult brook trout may also inhabit lentic areas such as lakes and beaver ponds, which may have much finer substrates (e.g., Chisholm *et al.* 1987).

(4) Cover

Brook trout are often found near cover, and this habitat variable may often limit trout production in streams (Boussu 1954; Lewis 1969; Hunt 1971; Fausch and White 1981; Cunjak and Power 1986, 1987; Lambert and Hanson 1989). Riley *et al.* (1992) found that the number of trout immigrating to a stream reach was related to the amount of cover present. Nestler *et al.* (1985) found that most brook trout in a southern river were associated with cover. Stream improvement measures which increase cover have been shown to result in increased brook trout biomass in streams (Riley and Fausch 1995). The importance of cover to juvenile brook trout may depend on fish size (Grant and Noakes 1987). Overgrown stream banks can benefit from removal of some overhanging vegetation, a technique which has been used successfully in Wisconsin (Hunt 1993).

(5) Temperature

Water temperature is considered one of the most important factors limiting brook trout distribution (MacCrimmon and Campbell 1969). Temperatures in the range of 0.0-24.0°C are suitable conditions for survival, but the optimum temperature is between 11.0 and 16.0°C (Jirka and Homa 1990). Giuttina and Garton (1982) used brook trout as an example in proposing a more ecologically appropriate measure of the range of temperatures over which a fish will perform various activities. Power (1990) tried to use temperature relations to predict how salmonid species would respond to climate change in Quebec and Labrador.

3.3 Brown Trout

The brown trout is native to Europe and western Asia and was introduced to North America in the late 1800's (Scott and Crossman 1973). The species has been introduced widely in North America since then (MacCrimmon and Marshall 1968) and is found in most Canadian provinces and in virtually all states of the U.S. that contain native trout populations. Both resident and anadromous populations may exist in the same catchment, but anadromous populations are less common in North America (Raleigh *et al.* 1986).

In Newfoundland, the brown trout was first introduced in ponds and lakes near St. John's and later in ponds on the Avalon Peninsula (Scott and Crossman 1964). Presently, the species is abundant in numerous river systems on the Avalon Peninsula. Their distribution seems to be dependent on climate, habitat variables and water chemistry (Gibson and Cunjak 1986) in that brown trout are not found in some rivers adjacent to rivers with abundant populations of the species, nor are populations found in rivers and nearby bays beyond the Avalon Peninsula (Nyman 1970; Gibson 1988).

3.2.1 Spawning, Incubation and Emergence

Brown trout spawn in the fall, usually in running water, the exact timing varying with latitude and other factors (Scott and Crossman 1973). In Norwegian rivers where brown trout are sympatric with Atlantic salmon, brown trout spawn earlier than salmon (Heggberget *et al.* 1988). Spawning behaviour is similar to that described for Atlantic salmon (Jones and Ball 1954). Brown trout do not appear to prefer areas of groundwater influx for spawning (Hansen 1975), as do brook trout (see above). They have been observed spawning in areas with and without groundwater seepage (Witzel and MacCrimmon 1983). Physical characteristics of spawning sites are quite variable, with velocities ranging from 24-70 $cm \cdot s^{-1}$, and depths from 6-60 cm (Smith 1973; Shirvell and Dungey 1983; Witzel and MacCrimmon 1983; Heggberget *et al.* 1988; Grost *et al.* 1990; Beard and Carline 1991). The minimum velocity for spawning has been reported to be between 12-20 $cm \cdot s^{-1}$ (Crisp and Carling 1989; Grost *et al.* 1990). Brown trout prefer areas dominated by larger substrates, specifically gravel 10-20 cm in diameter (Frost and Brown 1967; Shirvell and Dungey 1983; L'Abée-Lund 1991) for spawning, although mean gravel size of 80 mm has been reported (Ottaway *et al.* 1981). However, substrate characteristics may be less important than depth and velocity in spawning site choice (Shirvell and Dungey 1983; Grost *et al.* 1990). Suitable spawning gravel, may be relatively rare in very high-gradient streams (Kondolf *et al.* 1991). Gravel size is an important determinant of survival to emergence. Optimal survival to emergence decreases as the amount of fine sediment increases (Witzel and MacCrimmon 1982). Greatest alevin emergence survival was reported at 18.0 mm gravel (Olsson and Persson 1986). The size of the spawning gravel does not appear to be related to fish length (Ottaway *et al.* 1981; L'Abée-Lund 1991). Spawning migrations occur when temperatures range from 6-10°C (Davies and Sloan 1987).

Suitable temperatures for incubation of brown trout fry range from 2-13°C (Raleigh *et al.* 1986), and the minimum dissolved oxygen concentration for development is 4.5 ppm (Embody 1934). Brown trout require less time for development at low temperatures (<8°C) than do Atlantic salmon (Jensen *et al.* 1989).

3.3.2 Juveniles and Adults

Brown trout fry disperse soon after emerging and become territorial (Kalleberg 1958; Mortensen 1977), tending to occupy areas with coarse substrate (Heggenes 1988c). Estimates of the optimal temperature for fry growth ranges from 6-15°C (Raleigh *et al.* 1986). Habitat requirements often change as trout mature (Glova and Duncan 1985). Fry are often found in shallow water near stream margins (Lindroth 1955; Jones 1975) with coarse substrate (Glova and Duncan 1985), and may occupy deeper water and higher velocities during the day than at night (Harris *et al.* 1992). Glova and Duncan (1985) observed that in New Zealand rivers, juveniles (>55 mm) tend to occupy waters with depths >30 cm, water velocity greater than 30 $cm \cdot s^{-1}$ and often in areas where there is white water around boulders, small pools, debris, or submerged riparian growth. The optimum temperature range for juvenile brown trout is 4-19°C, the optimum growth temperature is 13°C, and mortality begins to occur above 25°C (Elliott 1975, 1981). Mortality occurs at pH levels below 5 (Grande *et al.* 1978). Grande *et al.* (1978) note that anadromous brown trout may be more sensitive to pH levels than landlocked brown trout.

Large brown trout (>400 mm in length) show seasonal patterns of habitat choice. In spring-summer months, these fish are found downstream in cold waters, where gravel substrate is present for spawning. In the autumn and winter months, large trout are more likely to be found upstream where water velocities are slower and deeper (Clapp *et al.* 1990).

3.3.3 Habitat Variables

(1) Water Velocity

Brown trout have been observed to occupy positions with mean water velocities ranging from 0-140 $cm \cdot s^{-1}$ (Baldes and Vincent 1969; Shirvell and Dungey 1983; Bachman 1984; Cunjak and Power 1986; Heggenes and Saltveit 1990; Rincon and Lobon-Cervia 1993). However, Heggenes and Saltveit (1990) found that brown trout preferred mean water velocities ranging from 10-15 $cm \cdot s^{-1}$ and were never found in waters with mean water velocities > 100 $cm \cdot s^{-1}$. Individuals may occupy faster water as they grow larger (Bohlin 1977; Cunjak and Power 1986), and fry may be found in velocities ranging from 0-18 $cm \cdot s^{-1}$ (Harris *et al.* 1992). Heggenes and Traaen (1988) noted that the critical water velocities for brown trout fry varied with water temperatures; as the temperature increased, the critical water velocities were higher. Additionally, salmonids beginning the free-feeding stage are washed out downstream at water velocities ranging from 10-25 $cm \cdot s^{-1}$. Water velocities selected by brown trout may change seasonally (Cunjak and Power 1986; Harris *et al.* 1992; Rincon and Lobon-Cervia 1993) and between day and night (Harris *et al.* 1992). Large brown trout (>400 mm long) were found in water velocities of 10 $cm \cdot s^{-1}$

(Clapp *et al.* 1990). In general, brown trout select relatively slow water in which to forage and rest (Heggenes 1988d).

(2) Water Depth

Shuck (1943) noted that juvenile brown trout were more abundant in riffle areas of a New York stream, while larger individuals were more numerous in deeper areas. Water depths occupied by brown trout range from 10-115 cm (Shirvell and Dungey 1983; Bachman 1984; Cunjak and Power 1986; Heggenes 1988c; 1988d; Heggenes and Saltveit 1990; Rincon and Lobon-Cervia 1993). Baldes and Vincent (1969) state that juvenile brown trout avoid areas with depth less than 5 cm. Heggenes (1988b) observed that there is a negative correlation between shallow water (<5 cm) and yearling distribution, whereas yearling distribution is positively related to water depths of 10-25 cm. Brown trout fry tend to occupy shallower water than older juveniles, and are often found near stream margins (Lindroth 1955; Jones 1975; Bohlin 1977). Larger trout occupy deeper habitats where the stream flow tends to be lower (Heggenes 1988a, 1988b). Trout greater than 400 mm were observed at water depths greater than 30 cm (Clapp *et al.* 1990). Juvenile brown trout were observed to occupy deeper water than Atlantic salmon parr in a Scottish stream (Egglishaw and Shackley 1982). Brown trout avoided using deep pool habitats in the presence of pike, and occupied shallower stream habitats (Greenberg 1992). Brown trout fry may move into shallower water near stream margins at night in order to avoid predation by larger conspecifics (Harris *et al.* 1992).

(3) Cover

Cover may be the most important variable determining the spatial distribution of brown trout in streams (Lewis 1969; Devore and White 1978; Nielsen 1986; Wesche *et al.* 1987b; Jowett 1990; but see Hartzler 1983; Bachman 1984). Nielsen stated that cover could account for >70% of the variation in brown trout density in some Danish streams. Brown trout are often found associated with cover (Hartman 1963; Butler and Hawthorne 1968; Lewis 1969; Egglishaw and Shackley 1982; Cunjak and Power 1986; Heggenes 1988b; Hesthagen 1988), which may limit brown trout populations in streams (Boussu 1954; Nielsen 1986; Wesche *et al.* 1987b; Thorn 1992; Rincon and Lobon-Cervia 1993). Yearlings avoid areas with no cover (Heggenes 1988b). Brown trout may use cover more in winter, and juveniles may hide in the substrate, like Atlantic salmon (Hartman 1963). Trout less than 17 cm do not require cover to establish residency in streams, however, for all trout sizes, as the amount of cover increased, the number of trout increased in the stream (Mesick 1988). Increases in brown trout biomass have been observed after the addition of artificial cover in some cases (Boussu 1954; Hunt 1993) but not in others (Hartzler 1969).

(4) Substrate

Relatively little information is available on the substrate preferences of wild brown trout. Brown trout are usually found over coarse substrates (Raleigh *et al.* 1986; Heggenes 1988b; Rincon and Lobon-Cervia 1993). Heggenes (1988a) notes that brown trout avoided areas with smooth bedrock substrate. Large brown trout (>400 mm) may prefer silt substrate (Clapp *et al.* 1990). Substrate may be less important than velocity or depth in

habitat use by brown trout (Rincon and Lobon-Cervia 1993). Jowett (1992) found that the abundance of large brown trout in New Zealand rivers was negatively correlated with the percentage of sand substrate. Yearling brown trout prefer substrate ranging from 64-256 mm (Heggenes 1988b).

(5) Temperature
Minimum water temperature may be a significant factor determining habitat preference for brown trout (Jowett 1990). Temperatures less than 4.5°C reduce the tendency of young salmonids to migrate (Ottaway and Clark 1981). Laboratory tests show that optimal temperature for feeding ranges from 4-19°C; optimal temperature for growth is 13°C (Jensen *et al.* 1989). Nettles *et al.* (1987) report that trout in Lake Ontario occupied water with temperatures ranging from 8-18°C.

3.4 Arctic Char

The Arctic char displays more diversity in morphology, life history and habitat use than either the Atlantic salmon, the brown trout or the brook trout. This diversity makes it difficult to define habitat preferences unless they are stock specific (e.g., see Sandlund *et al.* 1987). The scarcity of data, especially in North American juvenile stages compounds this problem. The Arctic char has a circumpolar distribution in the northern hemisphere and is found in nearshore marine waters, lakes and rivers in North America, northern Europe, Scandinavia, Iceland, Greenland, and northern Asia. Landlocked populations occur farther south than anadromous char, including northern New England, and eastern Canada (Scott and Crossman 1975; Scott and Scott 1988). Landlocked Arctic char are found throughout insular Newfoundland, Labrador, eastern Quebec and throughout northern Canada. Anadromous Arctic char reach their southern limit in insular Newfoundland (Scott and Scott 1988) occurring at the northern tip of the Great Northern Peninsula (Dempson 1982). Otherwise, the range of anadromous char in the province is concentrated in central coastal Labrador (Scott and Scott 1988). The species is largely replaced by Atlantic salmon and brook trout in southern Labrador (Dempson 1982), and in northern Labrador, the precipitous terrain limits the available habitat.

3.4.1 Spawning, Incubation and Emergence

In arctic waters, spawning normally takes place in September or October. Populations farther south may spawn as late as November or December in Newfoundland. The female prepares the nest where the eggs are deposited and fertilized by an attendant male.

Spawning occurs during the day over gravel or rocky shoals in lakes, and in pools in streams and rivers at depths of 1.0-4.5 m (Scott and Crossman 1975). In the Fraser River, nests were observed in depths ranging from 0.5-1.5 m (Dempson 1982). Cunjak *et al.* (1986) observed that substrate preference for redds was shallow water, heterogenous substrates (1-15 cm diameter range) with moderately strong surface water velocities. The age of sexual maturity varies (Riget *et al.* 1986). Females spawn every second to third

year. Southern populations are known to spawn every year (Scott and Crossman 1975).

The average water temperature for spawning is 4°C, however in the Fraser river, water temperatures recorded during the spawning season ranged from 1-3°C (Dempson 1982). In the Koroc River, in northeastern Quebec, the average water temperature was recorded at 6.2°C (Cunjak *et al.* 1986). At water temperatures above 7.8°C, eggs will not survive. Fertilized eggs develop over the winter buried in gravel and exposed to temperatures ranging from 0-2.2°C. The eggs are believed to hatch in early April, however the fry's emergence from the gravel does not take place until the breakup of ice in mid-July, at which point the fry are about 25 mm long (Scott and Crossman 1975). Optimum temperature range over which initial feeding occurs is 3-16°C and the optimum temperature range for growth is 11-14°C (Jensen *et al.* 1989).

3.4.2 Juveniles and Adults

Fry exhibit relatively slow growth in their early years. In the Fraser River, northern Labrador, annual growth increments for the first two years were 2.5 cm, and 3.5 $cm \cdot yr^{-1}$ for the third and fourth years and Arctic char averaged length of 12.5 $cm \cdot yr^{-1}$ in their third year and 16 $cm \cdot yr^{-1}$ in their fourth year (Dempson 1982; Dempson and Green 1985). More rapid growth was found in ages five to eight years (corresponding to stages that include seaward migrations) but size at age still tended to be below other North American populations.

Anadromous char that overwinter in lakes begin their seaward migration before or during ice breakup with the run usually ending in late July and return in late autumn (Scott and Crossman 1975). In Nain, Labrador, downstream migration occurs in late May and early June, while upstream migration begins in July and peaks in August (Dempson 1982; Dempson and Green 1985). Adults migrate first followed by first run juveniles (Scott and Crossman 1975; Dempson 1982; Näslund 1990).

The age and size of juvenile anadromous char on their first migration to sea can vary. In general, young char remain in fresh waters until they are 15.2-20.3 cm long. In Frobisher Bay, it was reported that fish are 5-7 years old at this size when the young char make their first migration (Scott and Crossman 1975). In Nain, Labrador, most juveniles migrate to sea at 4-5 years, the youngest are age 3+ and 12-17 cm (Coady and Best 1976). The smallest migrant recorded in the Fraser River was 8.7 cm, 3+ year (Dempson and Green 1985).

In general, the growth rates of Arctic char are slow (Scott and Crossman 1975). The first increase in growth occurs during the char's first migration to sea (Dempson 1982). Growth rates may be dependent on sea temperature and food supply (Berg and Berg 1989). Char grow better at lower temperatures; above 10°C growth rates declined (Berg and Berg 1989).

3.4.3 Habitat Variables

(1) Water Velocity
Spawning has been observed where mean water velocities were reported as 22 to 48 $cm \cdot s^{-1}$ at three sites (Cunjak *et al.* 1986). Other spawning activity occurs in lotic habitats. Heggberget (1984) reported that in two north Norwegian streams, where Arctic char were sympatric with Atlantic salmon and brown trout, between 70-85% of the char were found at velocities below 10 $cm \cdot s^{-1}$.

(2) Water Depth
In sympatry, Arctic char lived alongside brown trout near to the banks and Atlantic salmon in deeper water in two north Norwegian streams (Heggberget 1984). Over 90% of the Arctic char were in water <20 cm deep (Heggberget 1984). In night observations, Arctic char in the Koroc River were often observed in very shallow water, mean depths were generally <20 cm but depended on the slope of the shoreline, and fish were close to shore, the mean distance <90 cm (Stenzel and Power 1991).

(3) Substrate
Substrate preference for juvenile Arctic char varies depending on activity and time of day. Active char gradually change preference from gravel to rubble and become more active during daylight hours by late summer (Adams *et al.* 1988). The different size groups of Arctic char show habitat and food segregation (L'Abbee-Lund *et al.* 1992; Riget *et al.* 1986).

(4) Temperature
Optimal temperature for feeding ranges from 3-16°C; optimal growth temperatures ranges from 11-14°C (Jensen *et al.* 1989).

4.0 HABITAT MODELS

The preceding section reviews the general habitat requirements of the four salmonid species found in Newfoundland and Labrador. Many attempts have been made to combine specific habitat requirements into mathematical relationships, or models, which describe the relationship between fish abundance, density or location to habitat variables. These models are generally of two types: macrohabitat models and microhabitat models. Macrohabitat models (e.g., Binns and Eiserman 1979; Bowlby and Roff 1986; Fausch *et al.* 1988) attempt to determine the relationship between fish abundance, density, biomass, or production and broad-scale features of streams or stream reaches (e.g., canopy cover, discharge variability, width, etc.), while microhabitat models attempt to determine the fine-scale physical characteristics (e.g., velocity, depth, substrate) of positions chosen by fish for feeding, spawning or resting. Successful macrohabitat models would be useful for identifying reaches or streams where fish would be most abundant, or for predicting abundance (or density, biomass or production) of fish in a reach given habitat

characteristics. Microhabitat models are used to identify habitat requirements of species, and are often used as part of the Instream Flow Incremental Methodology (IFIM) to predict habitat quality in stream reaches at varying streamflows. Some studies use a combination of macro- and microhabitat approaches (Trial 1989; Bozek and Rahel 1991), and some authors make no distinction between the two types of models (e.g., Shirvell 1989a).

4.1 Scale

Habitat models fall into two general classes, but the division between them is not always obvious or clear-cut. Microhabitat models apply to the space a fish occupies at a particular instant in time using measures meaningful to an individual fish. Obviously the microhabitat of an individual changes during its life as the fish grows through different life history stages and perhaps, seasonally. Microhabitat models tend to focus on certain measurable parameters (often physical, but not necessarily) and take others applying to larger spacial areas, like river sections or whole rivers, for granted. Descriptions of microhabitats occupied by fish communities or species are blended means of individual microhabitats used by particular sizes or ages of fish during a specific time interval. Macrohabitat models try to describe habitat in broader terms and over much larger spacial areas. They divide rivers into more or less homogeneous reaches, each of which can be defined by a set of characteristics. The models are generalizations to the extent that streams and rivers are a continuous succession of reaches from sources to the sea connected by a unidirectional flow of water and materials. The river continuum concept (Vannote *et al.* 1980), the utility of which has been verified in numerous studies, guarantees that any classification of a river system into so-called homogeneous reaches is a compromise at best. However, there is no doubt that riffles, whether near the headwaters or downstream, are more similar to each other than they are to pools, even if the cycling of materials and stream processes may not be identical.

The distinction between the two scales of model should be borne in mind considering the two types of model. Because researchers often include macro-characteristics in their discussion of micro-models, the difference between the two types of model becomes somewhat blurred and sometimes arbitrary.

4.2 Macrohabitat Models of Abundance, Density, Biomass and Production

4.2.1 Atlantic Salmon

Several predictive models based on macrohabitat characteristics have been developed for Atlantic salmon (Table 1). Power (1973) made an early attempt to produce a macrohabitat model for salmonids in Norwegian streams, relating production to substrate characteristics, stream width, water quality and growing season. O'Grady (1993) found that parr abundance was reduced in areas with a dense overhead canopy that shaded the stream. Amiro (1993) found a relationship between parr density and stream gradient in Canadian rivers.

The most common type of macrohabitat model uses multiple linear regression to relate habitat characteristics of stream sites to fish abundance or density. Gibson *et al.* (1993) present several such models for Atlantic salmon parr density (also see Gibson 1993). These models are unusual in that they were developed within a single river (Northeast Brook at Trepassey, NFLD), while most models of this type are designed to estimate fish abundance or density among several rivers (Fausch *et al.* 1988). Some of the models presented by Gibson *et al.* (1993) appeared to explain a great deal of the variability in parr density among sites in Northeast Brook, but have been shown to be temporally unstable and, therefore, useless for prediction of parr density (Riley *et al.* 1993). Further investigation suggests that parr density in this river is unrelated to habitat characteristics, but is related to the proximity of spawning areas (S.C. Riley and R.L. Haedrich, unpublished data). Trial (1989) also found that habitat suitability was generally poorly correlated with Atlantic salmon parr density collected from 16 sites in the Saint John River drainage of New Brunswick. Terrell et al. (1995) developed a habitat suitability index (HSI) model for Atlantic salmon from a workshop attended by regional and international 'experts'. This model has not been applied or tested in the field.

Several authors have used habitat suitability criteria to describe relationships between macrohabitat variables and parr density or abundance (Table 2; Appendix A). Scruton and Gibson (1993) developed habitat suitability indices for macrohabitat data from 18 rivers in Newfoundland. Stanley and Trial (1992) present a model based partly on the work of Trial (1989), which includes a wide range of macrohabitat variables and is designed to apply to the entire North American range of Atlantic salmon. Moreau and Moring (1993) present a macrohabitat model for adult Atlantic salmon. They found that temperature, pool depth, cover, and proximity to spawning areas were important for adult use of holding pools prior to spawning.

4.2.1 Brook Trout

A number of studies present macrohabitat models of total trout biomass or abundance for fish assemblages that include brook trout and/or brown trout (Lewis 1969; Binns and Eiserman 1979; Bowlby and Roff 1986; Lanka *et al.* 1987; Kozel *et al.* 1989; Platts and Nelson 1989), but these are not appropriate here because of the inclusion of other trout species. Predictive brook trout models are summarized in Table 1. Gibson *et al.* (1993) present models which predict brook trout abundance from macrohabitat variables in a Newfoundland stream, but these models are flawed for the same reasons as described for the Atlantic salmon models (see above). Kozel and Hubert (1989) related brook trout abundance in Wyoming watersheds to elevation and stream size. Bozek and Hubert (1992) and Chisholm and Hubert (1986) found a relationship between the presence of brook trout and elevation, stream width, and gradient of stream reaches. These models are of questionable application to Newfoundland because of the greatly different physical conditions in these western streams, where brook trout are not native.

Raleigh (1982) presents macrohabitat suitability criteria for brook trout that are designed to be general for the entire North American range of the species (Table 3; Appendix B).

Vander Dussen *et al.* (1993) present macrohabitat models for brook trout in Ontario streams which were modified from other existing models, but these models were relatively unsuccessful in predicting brook trout biomass. Beauchamp *et al.* (1992) present logistic regression models which predict presence/absence of brook trout in Adirondack lakes based on water chemistry and watershed characteristics.

4.2.3 Brown Trout

Macrohabitat suitability models for brown trout are summarized in Table 4 and included in Appendix C. Jowett (1990, 1992) also developed several predictive models of brown trout abundance in New Zealand streams based on a variety of habitat variables (Table 1). He suggests that food (as measured by benthic invertebrate biomass) and suitable physical habitat (as measured by weighted usable area estimates developed from generalized microhabitat suitability curves) are the most important factors determining brown trout abundance in these streams. Wesche *et al.* (1987a) developed a model which related brown trout abundance to a cover rating and a measure of annual flow variation. Thorn (1988, 1992) developed models which also identified cover as an important variable determining brown trout density and biomass. Vander Dussen *et al.* (1993) describe macrohabitat models for brown trout that were developed from existing models and some field data in Ontario streams.

4.2.4 Arctic Char

Models for Arctic char have not been developed. Appendix D includes graphs of data that would contribute to the development of curves.

4.3 Microhabitat Suitability Criteria

4.3.1 Atlantic Salmon

Many of the observations of juvenile Atlantic salmon habitat use have not been formalized into habitat suitability criteria (e.g., Elson 1967; Gibson 1978; Symons and Heland 1978; Hearn and Kynard 1986) and are discussed in the first section of this report.

A number of different studies present microhabitat suitability criteria for Atlantic salmon (Table 5; Appendix E). Bietz (unpublished) provides suitability curves for spawning, incubation, fry, and parr in Top Pond Brook, Newfoundland. These curves were derived from limited literature data and are probably not generally applicable. Shirvell and Morantz (1983) developed curves for fry and parr in the Pembroke River, Nova Scotia. Morantz *et al.* (1987) present curves developed for six streams in Nova Scotia and New Brunswick, while DeGraaf and Bain (1986) developed curves for two rivers in Newfoundland. Heggenes (1991) and Heggenes and Saltveit (1990) present suitability criteria for depth, velocity and substrate for salmon parr in Norwegian streams. Heggenes *et al.* (1991) present frequency-of-use data for depth, substrate and velocity for small and large parr

based on two sampling methods. Heggenes (1990) presents generalized suitability curves for depth, velocity and substrate for small and large parr. These curves were based on a large number of literature references and are probably the most generally applicable curves available.

4.3.2 Brook Trout

Raleigh (1982) provides microhabitat suitability criteria for brook trout for a number of habitat variables (Table 6; Appendix F). Jirka and Homa (1990) developed suitability curves for velocity, depth, substrate and water temperature for brook trout using the "Delphi method", which is based on expert opinion and involves no local data collection.

4.3.3 Brown Trout

Raleigh *et al.* (1986) provide generalized microhabitat suitability criteria for all life stages of brown trout (Table 7; Appendix G). These criteria were developed for North American populations, but have been shown to have applicability elsewhere (Jowett 1992). Nehring and Anderson (1993) describe criteria for brown trout fry in Colorado streams. Lambert and Hanson (1989) present suitability curves for depth and velocity for brown trout, and discuss a variety of different methods of presenting this information. Harris *et al.* (1992) present suitability criteria for brown trout fry for depth, velocity and substrate.

4.3.4 Arctic Char

Microhabitat suitability models have not been developed for Arctic char. Appendix H contains tabular and graphic data that would be used to develop such curves.

5.0 DISCUSSION

5.1 Macrohabitat Models

A number of caveats are in order with regard to macrohabitat models. First, they can only predict the potential of a habitat to support a given biomass of fish. In this regard, it is important to note that these models assume that the only factor limiting populations is habitat. If this assumption is not true, then the models cannot be expected to accurately predict density or biomass from habitat variables (Terrell et al. 1995). For example, if trout density is limited by food availability (e.g., Gibson *et al.* 1984; Einarsson *et al.* 1990; Ensign *et al.* 1990) or the proximity of spawning areas (e.g., Benson 1953; Beard and Carline 1991), then macrohabitat models would not be expected to work. A number of studies suggest that factors other than habitat may affect the abundance and distribution of salmonids, including population density, food availability, water quality, predation, and competition (Egglishaw and Shackley 1977; Binns and Eiserman 1979; Elliott 1984a, 1984b; Morantz *et al.* 1987). Fish abundance varies seasonally (Hicks and Watson 1985)

and the dynamics of the habitat measures may not always reflect this. Macrohabitat models assume that the populations under consideration are at carrying capacity, an assumption which is unlikely to be the case in many situations, especially for Atlantic salmon. These models also assume that the abundance or density of fish at a given site is a good indicator of habitat quality, which may not always be true (e.g., Van Horne 1983). Moreover, if a stable relationship between habitat and abundance or density is to exist, fish must use different habitat types in the same proportion at different overall densities, which is unlikely to be the case in natural systems (T.P. Bult and S.C. Riley, unpublished data). Results from these types of models should, therefore, be viewed with caution.

Macrohabitat models for salmonids often fail to successfully predict abundance or density when applied outside of the areas where they were originally developed (Layher and Maughan 1985; Bowlby and Roff 1986; Scarnecchia and Bergersen 1987; Fausch *et al.* 1988; Shirvell 1989a), reflecting the fact that the variables that limit salmonid production vary among regions. This suggests that many habitat models may not be transferrable to areas other than the ones in which they were developed, and caution should be used when applying habitat criteria that were not locally developed or verified.

The current state of our knowledge of competitive interactions among salmonid species is not sufficient for prediction of the effects of one species on another (Fausch 1988). It is especially important to consider the effects of other fish species when developing suitability criteria for a fish species (Orth 1987). Suitability data for a given species that were developed in areas with an abundance of sympatric fish species may not apply in Newfoundland.

5.2 Microhabitat Models

Microhabitat models are designed to determine which variables are most important in habitat choice by fish, and are often used as a part of the Instream Flow Incremental Methodology (IFIM) developed by the U.S. Fish and Wildlife Service (Bovee 1982). In this procedure, Habitat Suitability Criteria (or habitat suitability curves - HSC), are determined and used by the physical habitat simulation (PHABSIM) program to determine indices of habitat quality in streams and to estimate habitat quality at different streamflows. The IFIM has been criticized on a number of grounds, including inaccuracies in hydraulic simulation by PHABSIM (Osborne *et al.* 1988), the potential for intentional manipulation of results by users (Gan and McMahon 1990), and a number of ecological and methodological considerations (Orth and Maughan 1982; Mathur *et al.* 1986; Hanson *et al.* 1987; Orth 1987; Conder and Annear 1987; Shirvell 1989b). Several studies indicate that PHABSIM does not adequately predict the habitat used by fish (Rimmer 1985; Irvine *et al.* 1987; Shirvell 1989b). Essentially, these models attempt to describe an extremely complex phenomenon - fish dispersion - based on relatively few observations that are usually made only during the day in a single season of the year in restricted locations. It is often suggested that a complex phenomenon such as fish habitat use cannot be adequately described by such limited observations (e.g., Mathur *et al.* 1986). It is especially important to note that these models assume that habitat is limiting the populations in question, and

the complex effects of other potential limiting factors (competing species, food abundance, predators) are usually ignored (see Orth 1987). Nevertheless, IFIM contains a sophisticated set of models to relate physical characteristics of streams to habitat quality for fishes, and has been widely used for stream habitat studies (Reiser *et al.* 1989; Jowett 1992; Nehring and Anderson 1993). Moreover, some recent studies have shown that IFIM can be successfully used to predict brown trout abundance in streams (Jowett 1992; Nehring and Anderson 1993). It is important to note, however, that few IFIM models have been properly verified or tested (Armour and Taylor 1991), and the general efficacy of this technique is therefore largely unknown.

An important consideration in using microhabitat information as part of an IFIM study is the transferability of habitat suitability criteria. Wide variability in results may occur from using different HSC (Shirvell 1989b), and some criteria may not be transferable among rivers even within a small geographic area (Thomas and Bovee 1993). It is therefore very important to determine the applicability of habitat suitability criteria for use in an area before applying them. For example, deGraaf and Bain (1986) showed that habitat suitability criteria for Atlantic salmon parr were significantly different between two rivers on the Avalon peninsula of Newfoundland. Heggenes (1991) suggests that the importance of different variables may depend on the type of habitat being studied within a given river. The importance of different variables would almost certainly be different in different rivers, given the large number of factors that affect habitat use (e.g., flow regime, temperature, predators, competing fish species, season, time of day, etc.) and the likelihood that they will differ among rivers. In developing suitability criteria for trout in California, Hanson *et al.* (1987) observed trout species in colder waters, and in small tributaries with low velocities. The habitat criteria of this study could be used on streams of similar order and species composition but should not be used for larger order streams with differing fish composition. The use of preference curves, which are designed to correct for the effects of differing habitat availability among sites, may improve transferability (Bovee 1982; Moyle and Baltz 1985), but deGraaf and Bain (1986) found differences in preference curves for Atlantic salmon between two adjacent Newfoundland rivers. There are methods for evaluating the transferability of habitat suitability criteria (Bovee 1986; Thomas and Bovee 1993) which should be applied before an analysis is attempted on a new site.

There are a number of potential limitations of using the IFIM in Newfoundland. The method is costly and requires well-trained personnel to conduct detailed fieldwork, particularly if site-specific habitat criteria are developed. The nature of Newfoundland streams makes the application of the method more difficult than elsewhere, since most streams are remote, ungauged, have complex channels, and are characterized by unstable flow regimes. The predominance of lacustrine habitat in many Newfoundland river systems also complicates things, since the IFIM is designed to apply to riverine habitats only.

6.0 RECOMMENDATIONS

Given the large number of uncertainties associated with habitat models (see above), it is our recommendation that a large amount of effort be put into testing any models that are developed in Newfoundland before they are applied. Although many habitat models have been developed for salmonids throughout North America, very few have been tested (Fausch *et al.* 1988; Armour and Taylor 1991). Moreover, the atypical hydrologic conditions and fish fauna of Newfoundland make it unlikely that models like those used elsewhere will apply. Therefore, we recommend that any models that are developed be tested with independent data from rivers other than those in which they were developed, and also with data from the same river in other years.

Model testing also applies to the assumptions that are made by the models in question. For example, habitat models assume that populations are limited by habitat, which may or may not be true (see above). This assumption, along with many others, should be tested before models are applied in Newfoundland. Recent data collected from a Newfoundland stream suggests that juvenile Atlantic salmon density may not be related to the most common variables (depth, velocity, substrate and cover) used in habitat models (S.C. Riley, T.P. Bult, and R.L. Haedrich, unpublished data). We recommend that the following specific studies be undertaken before any habitat model is used for assessment purposes in the province.

1. Does habitat limit salmonid populations in Newfoundland? This is a critical assumption of all habitat models, and one that is rarely tested. It is conceivable, due to the cold climate and relatively low productivity of Newfoundland streams, that salmonid populations here might be food-limited. It has been suggested that benthic invertebrate biomass may be related to trout abundance in Newfoundland (Orr *et al.* 1990) and elsewhere (Bowlby and Roff 1986; Jowett 1992), and this variable should be incorporated in any macrohabitat models that are developed. Replicated field experiments designed to test the effects of large-scale habitat manipulations should be performed on several streams in Newfoundland. Habitat conditions in these streams should be modified based on criteria described in this report, and the effects on salmonid populations should be monitored for several years afterward.

2. If habitat is limiting, during which season is this limitation most important? Very little stream sampling has been done year-round in Newfoundland, for obvious reasons. It is, however, important to determine if habitat may be limiting during seasons other than summer (cf. Harris *et al.* 1992). Data should therefore be collected during as many months of the year as practical in order to identify the time when habitat is most limiting.

3. Do spatially and temporally stable HSI relationships exist for salmonid species in Newfoundland streams? HSI curves should be developed for each of the species of interest in several Newfoundland streams, and these curves should be tested against data obtained from other streams. The temporal stability of the curves should be tested using data from the same streams, but collected in different years and different seasons. The

same habitat variables may not be important in different streams or in different seasons or years. As many habitat variables should be examined as is practical, and they should be chosen for each species from those presented here. Good habitat models cannot be produced if strong relationships between fish populations and habitat do not exist.

4. How important is lacustrine production to salmonid stocks in Newfoundland watersheds? Very little good research has addressed this question in Newfoundland, considering the amount of this type of habitat that occurs here. Some attention should be paid to measuring habitat use in lacustrine areas and attempting to determine what proportion of the population of a given study river occupies such habitat.

5. Does a positive linear relationship exist between WUA and salmonid biomass in Newfoundland streams? This is a critical assumption of the IFIM. WUA and salmonid biomass should be estimated in several streams in several seasons and years to determine if such a relationship exists and how it varies spatially and temporally.

6. How well does PHABSIM estimate habitat conditions in Newfoundland streams at varying discharges? Habitat data should be collected at a number of different discharge levels, and results compared to predictions from PHABSIM. The complex nature of stream channels and hydrologic conditions here require rigorous testing of the ability of the hydraulic model to adequately model habitat conditions.

7. Is it necessary to use a complex method such as the IFIM to model salmonid habitat use in Newfoundland streams? It has been suggested that juvenile Atlantic salmon habitat use can be modelled using relatively few variables (Caron and Talbot 1993), and it would be useful to determine if a simpler approach with fewer assumptions would apply in Newfoundland. This would require a careful analysis of the habitat use data that is collected as described above.

These specific recommendations go well beyond what is usually required of a standard habitat model application, but we feel that they are all important if these models are to be used in Newfoundland. The relative paucity of habitat use data from Newfoundland, along with the differences in the fish fauna and the complex, atypical hydrologic conditions, make extensive model testing and verification a necessity here. These factors also make it imperative that only locally-derived habitat use data should be used if habitat models are applied in Newfoundland, at least until it is determined that criteria from elsewhere are applicable. If IFIM applications are attempted here, strict attention should be paid to testing the transferability of criteria among rivers (Thomas and Bovee 1993), since it has been determined that habitat use may differ substantially among streams on the Avalon peninsula (deGraaf and Bain 1986). It should be noted that although the habitat models are intended to be used as management tools, the information that would be obtained during the testing that we propose would have considerable value to researchers, and could be integrated with research activities now being carried out in the province. The most important aspects of the application of these models is the validation of assumptions and the verification that the models are behaving as expected. The only way that these models can be improved is by rigorous testing.

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Table 1: Predictive models of abundance based on habitat characteristics for three species of salmonids.

Significant Variable(s)	Species	Life Stage	Explained Variance (r^2)	Reference
Stream Gradient	Atlantic salmon	parr (1+; 2+)	0.1 - 0.73	Amiro 1993
Max. Flood Height	Atlantic salmon	fry (0+)	0.32	Gibson *et al.* 1993
Chloride	Atlantic salmon	parr (1+)	0.42	Gibson *et al.* 1993
Velocity; Substrate; Instream Cover	Atlantic salmon	parr (2+)	0.52	Gibson *et al.* 1993
Bankside Vegetation	Atlantic salmon	fry (0+); parr (1+)	0.61 - 0.95	O'Grady 1993
Bankful Width	brook trout	> 100 mm	0.77	Kozel and Hubert 1989
Elevation; Stream Width; Stream Gradient	brook trout	All	NA	Bozak and Hubert 1992
Conductivity; Total Phosphorus; Max. Flood Height	brook trout	fry (0+)	0.52	Gibson *et al.* 1993
Calcium; Velocity; Total Phosphorus; Max. Flood Height	brook trout	1+	0.35 - 0.53	Gibson *et al.* 1993
Nitrate; Depth; Stream Width; Total Phosphorus; Max. Flood Height	brook trout	2+	0.33 - 0.57	Gibson *et al.* 1993
Max. Flood Height; Instream Cover; Conductivity; Total Phosphorus	brook trout	3+	0.54 - 0.81	Gibson *et al.* 1993
Weighted Usable Area; Instream Cover; Stream Gradient; % Sand; % Lake Area; Elevation; Development in Basin	brown trout	> 200 mm	0.88	Jowett 1992
Benthic Invertebrate Biomass; Weighted Usable Area	brown trout	> 200 mm	0.64	Jowett 1992
Instream Cover; Depth	brown trout		0.33 - 0.74	Nielsen 1986
Velocity; Pool Bank Shade; Bank Cover	brown trout	All	0.56	Thorn 1992
Bank Cover; Pool Bank Shade; Velocity	brown trout	All	0.42	Thorn 1992
Instream Cover; Annual Flow Variation	brown trout		0.51	Wesche *et al.* 1987

Table 2. Macrohabitat suitability models for Atlantic salmon

Parameter	Life Stage	Context	Reference
Overhanging cover	Fry	Nfld.; Nfld-minimum summer flow	Scruton and Gibson 1993; Terrell *et al.* 1995
	Parr	Nfld.	Scruton and Gibson 1993
Stream width	Fry	Nfld; Nfld-minimum summer flow	Scruton and Gibson 1993; Terrell *et al.* 1995
	Parr	Nfld	Scruton and Gibson 1993
Discharge	Fry	Nfld	Scruton and Gibson 1993
	Parr	Nfld	Scruton and Gibson 1993
Daily max. temperature	All	North America	Stanley and Trial 1992
Turbidity	All	North America	Stanley and Trial 1992
Oxygen saturation	All	North America	Stanley and Trial 1992
pH	All	North America	Stanley and Trial 1992
	Fry	Nfld-emergence	Terrell *et al.* 1995
Stream order	All	North America	Stanley and Trial 1992
Weighted useable area	Fry		Shirvell and Morantz 1983
	Parr		Shirvell and Morantz 1983
	Juvenile	Summer	Shirvell and Morantz 1983
Ice scar height	Fry	Nfld	Scruton and Gibson 1993
	Parr	Nfld	Scruton and Gibson 1993
Flood height	Fry	Nfld	Terrell *et al.* 1995
Habitat types	Fry	Nfld	Terrell *et al.* 1995
Stream flow	Fry	Nfld	Terrell *et al.* 1995
Percent dead water or impoundment		Nfld	Terrell *et al.* 1995
Percent drainage basin	Fry	Nfld	Terrell *et al.* 1995
Hardness		Nfld	Terrell *et al.* 1995
Biochemical oxygen demand	Fry	Nfld	Terrell *et al.* 1995
Nitrate	Fry	Nfld	Terrell *et al.* 1995

Table 2. Continued

Temperature	Spawning	North America	Stanley and Trial 1992
	Incubation	North America, between November 15 - May 1	Stanley and Trial 1992
	Parr	Newfoundland	Terrell *et al.* 1995
	All	North America, growing season, summer	Stanley and Trial 1992
Instream Cover	Fry	Newfoundland	Scruton and Gibson 1993
	Parr	Newfoundland	Scruton and Gibson 1993, Terrell *et al.* 1995; Heggenes and Saltveit 1990
Embeddedness	Incubation	Newfoundland	Terrell *et al.* 1995

Table 3. Macrohabitat suitability models for Brook Trout

Parameter	Context	Reference
Percent fines	North America, riffle run and spawning areas	Raleigh 1982
Percent Pools	North America, late growing season, low water period	Raleigh 1982
Dissolved Oxygen	North America, late growing season, low water period, and embryo development	Raleigh 1982
Thalweg Depth	North America, late growing season, low water period	Raleigh 1982
Percent stream area shaded	North America, between 1000 and 1400 hrs; streams < 50 m wide;	Raleigh 1982
Pool class	North America, late growing season, low flow period (Aug-Oct)	Raleigh 1982
pH	North America	Raleigh 1982
Average annual base flow regime	North America, late summer or winter flow period	Raleigh 1982
Rooted vegetation; stable ground cover	North America, summer (erosion control)	Raleigh 1982
Percent streambank vegetation	North America, summer	Raleigh 1982
Temperature	North America	Raleigh 1982; Jirka and Homa 1990
Instream Cover	North America	Raleigh 1982

Table 4. Macrohabitat suitability models for Brown Trout

Parameter	Context	Reference
Percent Pools	North America, late growing season, low water period	Raleigh 1982
Dissolved Oxygen	North America, late growing season, low water period, and embryo development	Raleigh *et al.* 1986
Percent stream area shaded	North America, between 1000 and 1400 hrs; streams < 50 m wide;	Raleigh *et al.* 1986
Pool class	North America, late growing season, low flow period (Aug-Oct)	Raleigh *et al.* 1986
pH	North America	Raleigh *et al.* 1986
Average annual base flow regime	North America, late summer or winter low-flow period	Raleigh *et al.* 1986; Wesche *et al.* 1987
Annual peak flow	North America	Raleigh *et al.* 1986
Rooted vegetation; stable ground cover	North America, summer (erosion control)	Raleigh *et al.* 1986
Percent streambank vegetation	North America, summer	Raleigh *et al.* 1986
Nitrate/Nitrogen	North America, late summer	Raleigh *et al.* 1986
Temperature	North America	Raleigh *et al.* 1986
Instream Cover	North America	Heggenes and Saltveit 1990; Raleigh *et al.* 1986

Table 5. Microhabitat suitability models for Atlantic Salmon

Parameter	Life Stage	Context	Reference
Velocity	Spawning	Newfoundland; North America	deGraaf and Chaput 1984, Bietz (no date); Stanley and Trial 1992
	Incubation	Newfoundland	Bietz (no date)
	Fry	Newfoundland; Newfoundland - column and nose velocity; North America; Maine	Scruton and Gibson 1993, Bietz (no date), Terrell *et al.* 1995; deGraaf and Chaput 1984; Stanley and Trial 1992, Shirvell and Morantz 1993; Trial 1989
	Juvenile	Newfoundland	Bietz (no date)
	Parr	Newfoundland; Newfoundland - column and nose velocity; North America; mean and snout velocity	Scruton and Gibson 1993; deGraaf and Chaput 1984; Shirvell and Morantz 1993; Heggenes 1990; Heggenes and Saltveit 1990
	Young-of-year	Newfoundland	Terrell *et al.*1994; Heggenes 1990
Depth	Spawning	Newfoundland	Bietz (no date)
	Fry	Newfoundland; North America; Maine	Scruton and Gibson 1993, deGraaf and Chaput 1984; Stanley and Trial 1992, Shirvell and Morantz 1993; Trial 1989
	Parr	Newfoundland; North America; Maine; large parr	Scruton and Gibson 1993, deGraaf and Chaput 1984; Stanley and Trial 1992, Shirvell and Morantz 1993; Trial 1989; Heggenes 1990; Heggenes and Saltveit 1990
	Young-of-year		Heggenes 1990
Substrate	Spawning	Newfoundland; North America	Bietz (no date); Stanley and Trial 1992
	Incubation	North America	Stanley and Trial 1992
	Fry	Newfoundland; Newfoundland - growing season, winter; North America; Maine	Scruton and Gibson, deGraaf and Chaput 1984; Terrell *et al.*1995; Stanley and Trial 1992, Shirvell and Morantz 1993; Trial 1989
	Parr	Newfoundland; North America; Maine	Scruton and Gibson, deGraaf and Chaput 1984; Stanley and Trial 1992, Shirvell and Morantz 1993; Trial 1989; Heggenes 1990; Heggenes and Saltveit 1990
	Young-of-Year		Heggenes 1990

Table 6. Microhabitat suitability models for brook trout

Parameter	Life Stage	Context	Reference
Velocity	incubation, juvenile; spawning, fry, juvenile, adult	North America-spawning areas; North America; California	Raleigh 1982; Jirka and Homa 1990; Hanson *et al.* 1993
Depth	juvenile; spawning, fry, juvenile, adult	North America; California	Jirka and Homa 1990; Hanson *et al.* 1993
Substrate	Spawning; juvenile	North America	Raleigh 1982; Jirka and Homa 1990
	spawning and egg development	North America	Raleigh *et al.* 1986
	juvenile	North America; North America - riffle-run areas for food production	Jirka and Homa 1990; Raleigh 1982
	fry, juvenile	winter and escape cover	Raleigh 1982

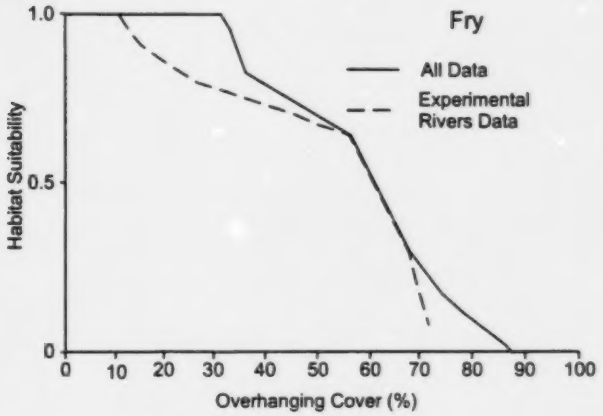
Table 7. Microhabitat suitability variables for brown trout

Parameter	Life Stage	Context	Reference
Velocity	all; young-of-year; all; parr; > 55 mm FL; adult and food producing habitat; all	North America; Douglas Creek, Wyoming; California;	Raleigh *et al.* 1986; Harris *et al.* 1992; Hanson *et al.* 1993; Heggenes and Saltveit 1990; Glova and Duncan 1985; Jowett 1992
Depth	all; young-of-year; spawning, fry, juvenile, adult; parr; > 55 mm FL; adult, food producing habitat	North America; Douglas Creek, Wyoming; California;	Raleigh *et al.* 1986; Harris *et al.* 1992; Hanson *et al.* 1993; Heggenes and Saltveit 1990; Glova and Duncan 1985; Jowett 1992
Substrate	all; young-of-year; > 55 mm FL; adult, food producing habitat	North America; Douglas Creek, Wyoming;	Raleigh *et al.* 1986; Harris *et al.*1992; Glova and Duncan 1985; Jowett 1992
	parr; fry and small juveniles	North America	Heggenes and Saltveit 1990; Raleigh *et al.* 1986

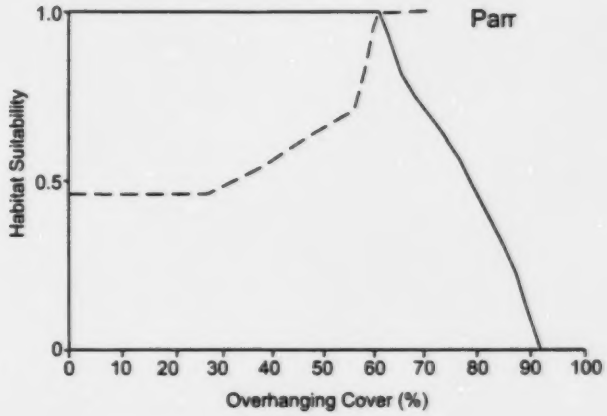
Appendix A

Macrohabitat suitability criteria for various life stages of Atlantic salmon

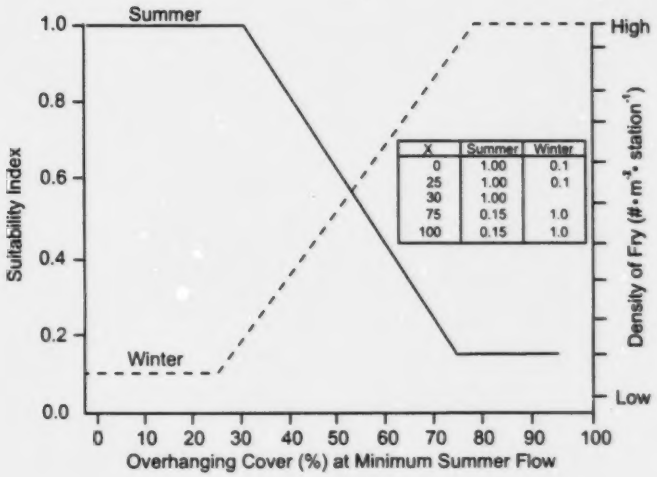
Overhanging cover suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993

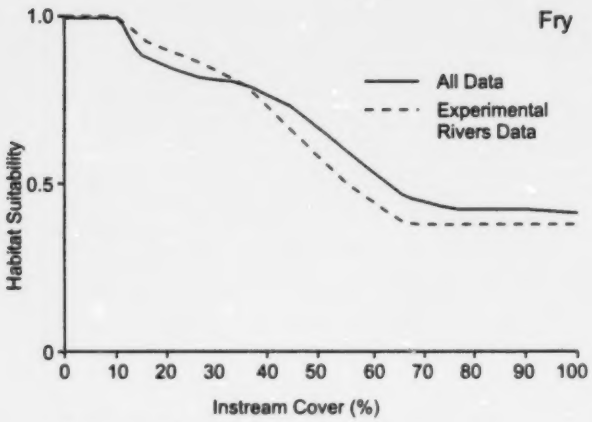


Scruton and Gibson 1993

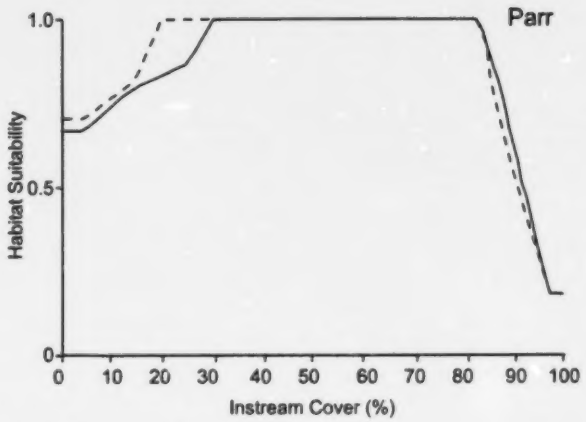


Terrell *et al.* 1995

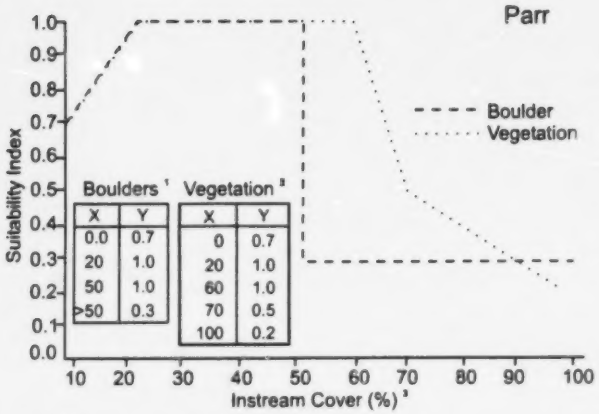
Instream cover suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993



Scruton and Gibson 1993



Boulders [1]

X	Y
0.0	0.7
20	1.0
50	1.0
>50	0.3

Vegetation [2]

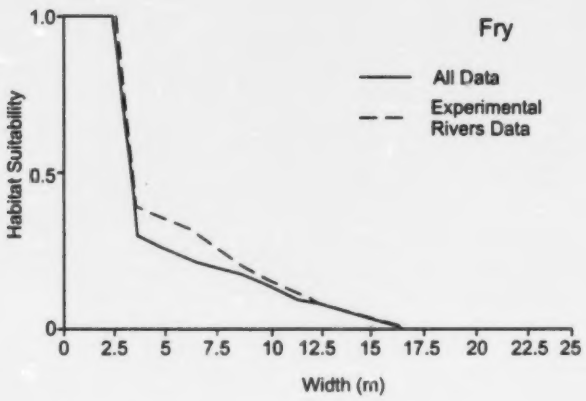
X	Y
0	0.7
20	1.0
60	1.0
70	0.5
100	0.2

1 Submerged and/or emergent boulders
2 Vegetation includes large woody debris
3 Percent of area with cover above the plane of the dominant substrate

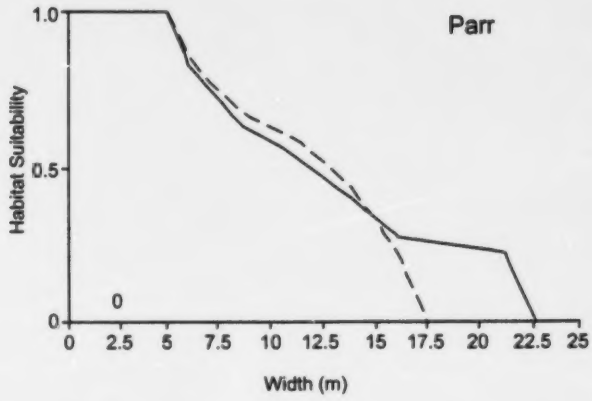
Note: if boulders are > 50% then suitability for instream cover is the same as for dominant substrate

Terrell *et al.* 1995

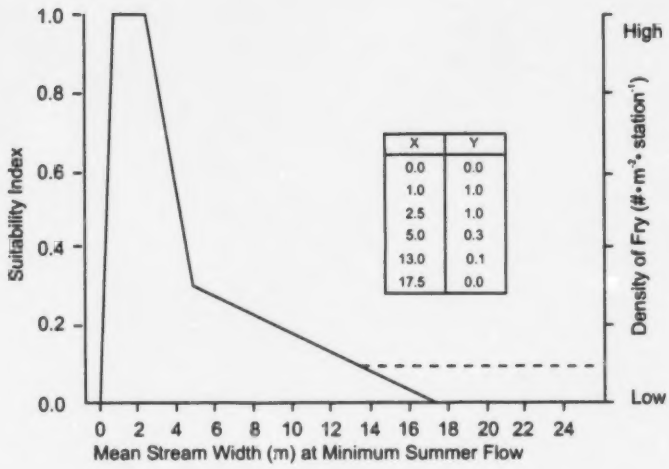
Stream width suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993



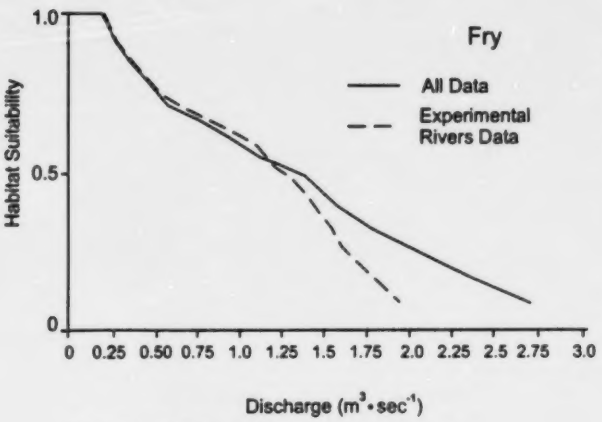
Scruton and Gibson 1993



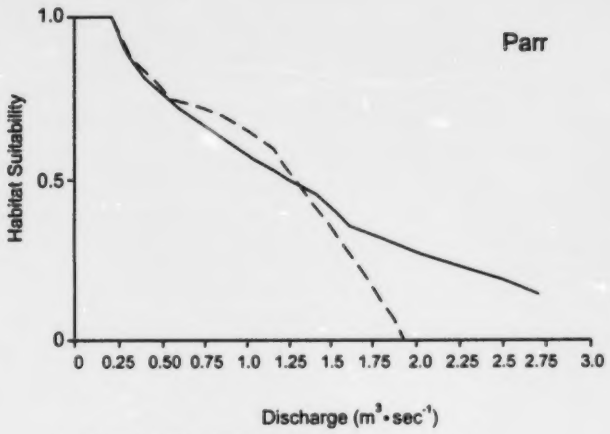
X	Y
0.0	0.0
1.0	1.0
2.5	1.0
5.0	0.3
13.0	0.1
17.5	0.0

Terrell *et al.* 1995

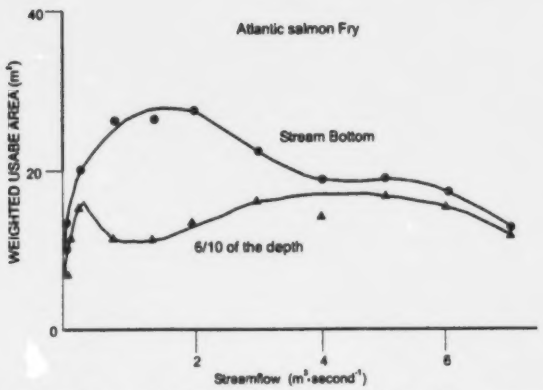
Discharge suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993

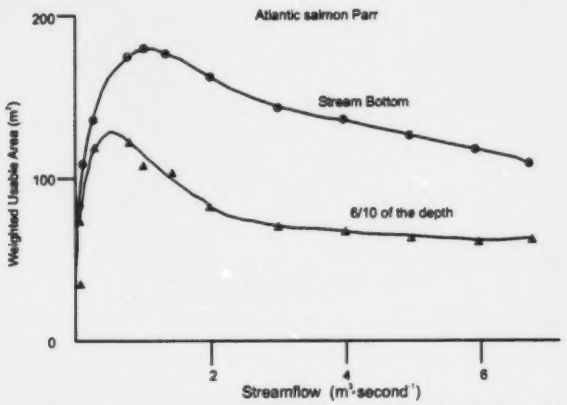


Scruton and Gibson 1993



The amount of weighted usable area available to Atlantic salmon fry at the stream bottom (●—●) or at 6/10 of the depth (▲—▲) for streamflows less than bankfull.

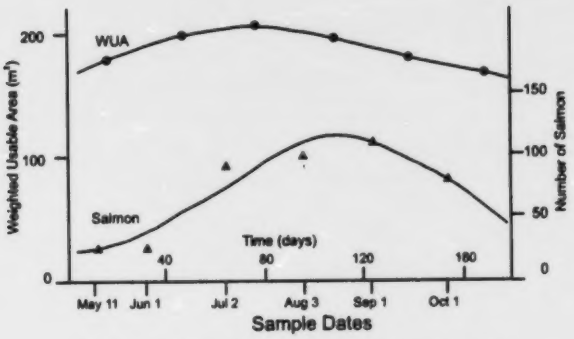
Shirvell and Morantz 1983



The amount of weighted usable area available to Atlantic salmon parr at the stream bottom (▲—▲) and at 6/10 of the depth (● —●) and number for streamflows less than bankfull.

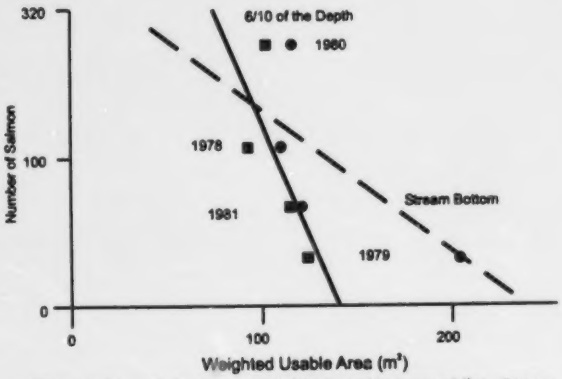
Shirvell and Morantz 1983

Weighted usable area suitability criteria for various life stages of Atlantic salmon



The relationship between weighted usable area at the stream bottom (●—●) and number of juvenile Atlantic salmon (▲—▲) during summer.
Number of Atlantic salmon = 1.00 WUA (m^2) - 115.9; r^2 =

Shirvell and Morantz 1983



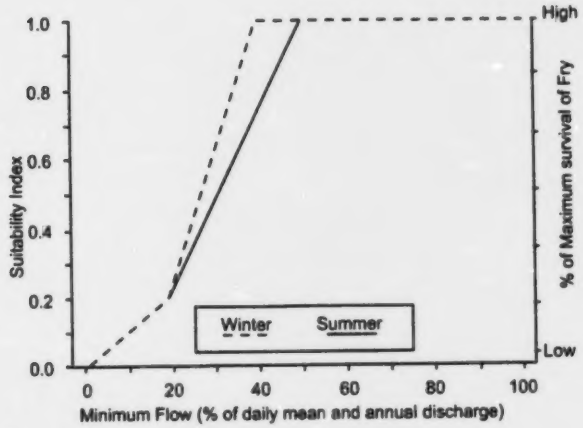
The relationship between weighted usable area at the stream bottom (●—●) or at 6/10 of the depth (■—■) and the number of juvenile Atlantic salmon at the summer low-streamflow period from 1978 to 1981.

Stream bottom:
Number of Atlantic salmon = -153 WUA (m^2) + 365.2; r^2 = 0.49.

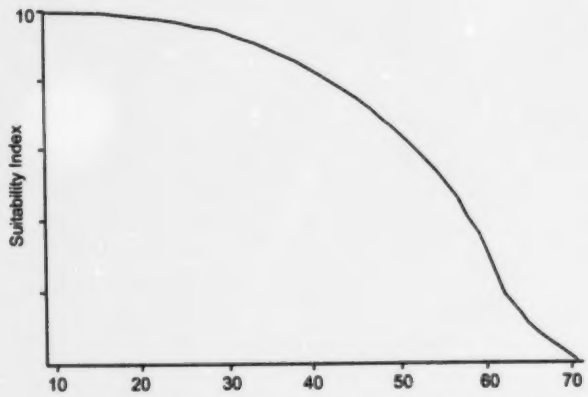
6/10 of the depth:
Number of Atlantic salmon = -4.69 WUA (m^2) + 663.1; r^2 = 0.50

Shirvell and Morantz 1983

Flow characteristics suitability criteria for various life stages of Atlantic salmon



Terrell *et al.* 1995



Terrell *et al.* 1995

pH suitability criteria for various life stages of Atlantic salmon

Minimum pH: The frequency at which critical pH levels are reached as measured during episodes of acid runoff during 3 day periods.

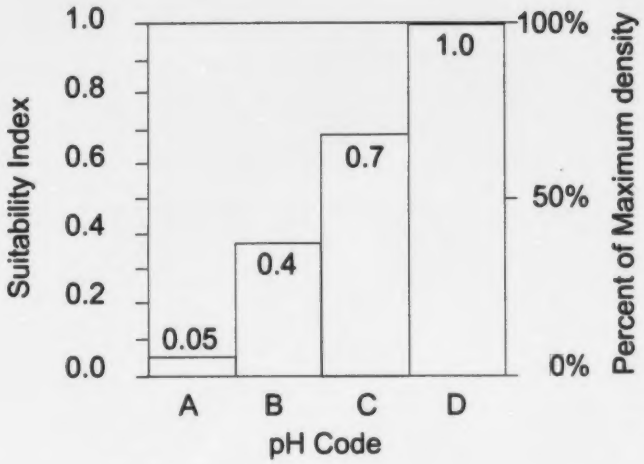
A pH below 4.0 at least once annually

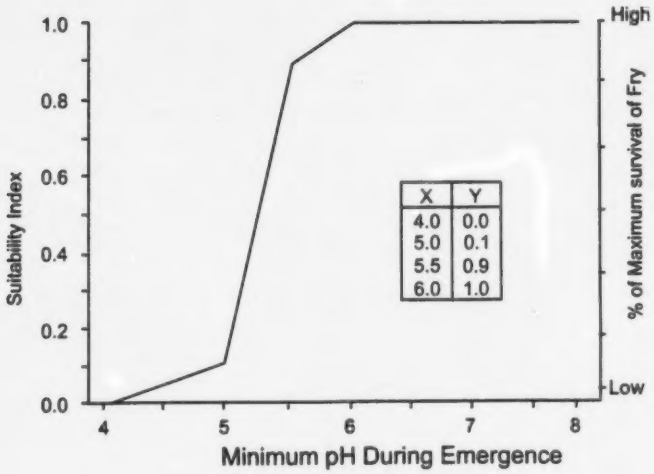
B pH 4.0 to 5.5 at least once annually

C pH occasionally falls below 5.5, but never below 5.0

D pH always 5.5 to 6.8

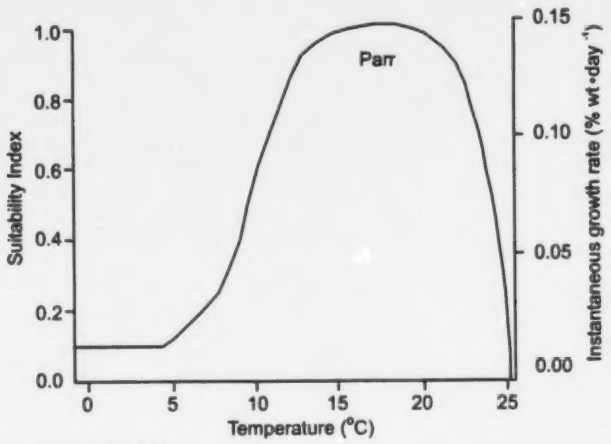
Stanley and Trial 1992
Terrell *et al.* 1995



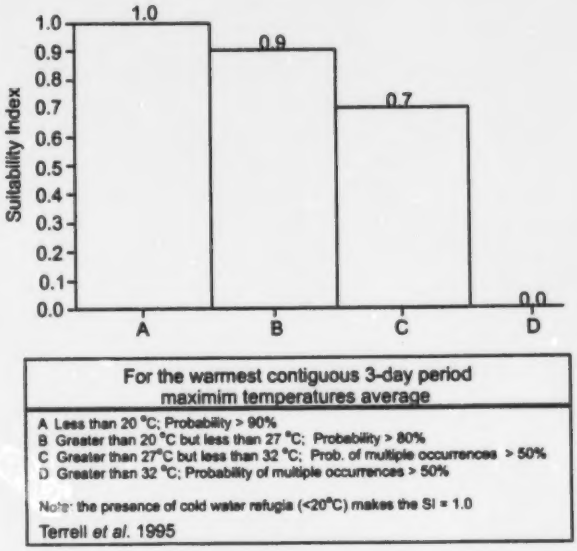


Terrell *et al.* 1995

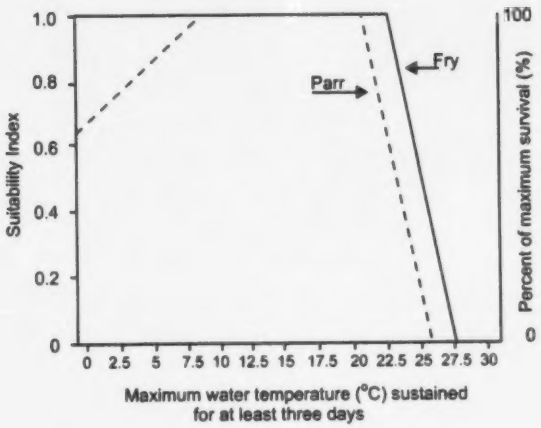
Temperature suitability criteria for various life stages of Atlantic salmon



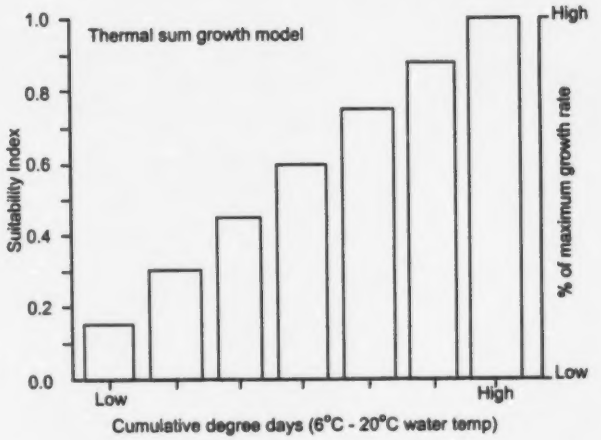
Terrell *et al.* 1995



For the warmest contiguous 3-day period maximim temperatures average
A Less than 20 °C; Probability > 90%
B Greater than 20 °C but less than 27 °C; Probability > 80%
C Greater than 27°C but less than 32 °C; Prob. of multiple occurrences > 50%
D Greater than 32 °C; Probability of multiple occurrences > 50%
Note: the presence of cold water refugia (<20°C) makes the SI = 1.0
Terrell *et al.* 1995

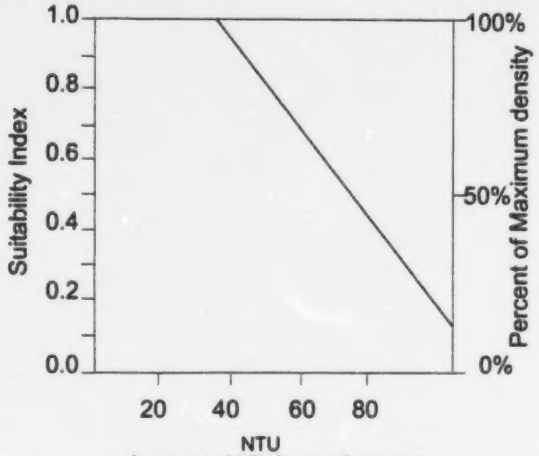


Terrell *et al.* 1995
(From Elliott 1991)



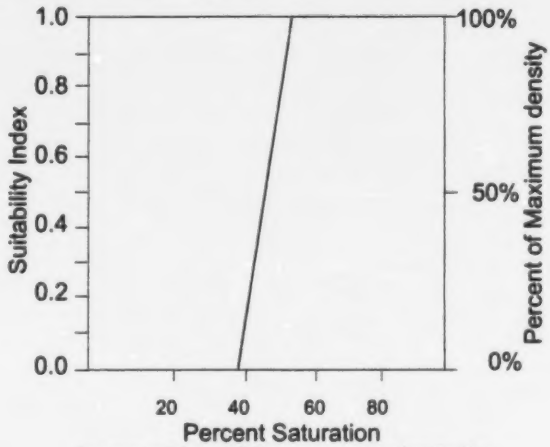
Wright *et al.* 1991

Other water quality parameters for various life stages of Atlantic salmon



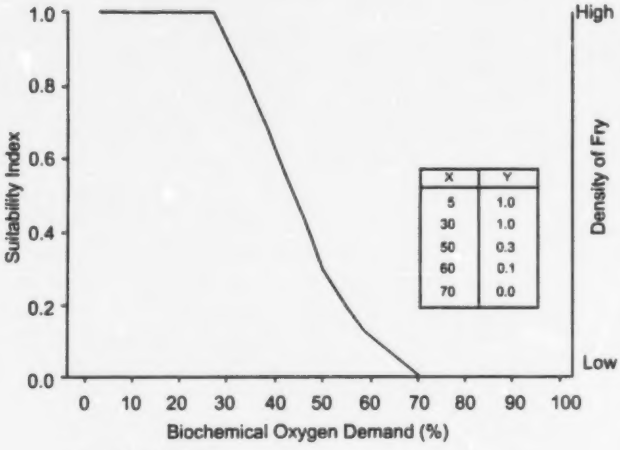
Average turbidity by month over as much of the year as possible.

Stanley and Trial 1992



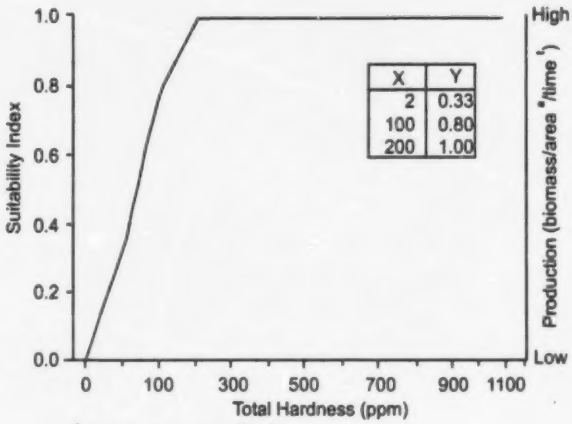
Average minimum daily oxygen saturation for the 3-day period with the lowest percent saturation during the summer.

Stanley and Trial 1992



X	Y
5	1.0
30	1.0
50	0.3
60	0.1
70	0.0

Terrell *et al.* 1995

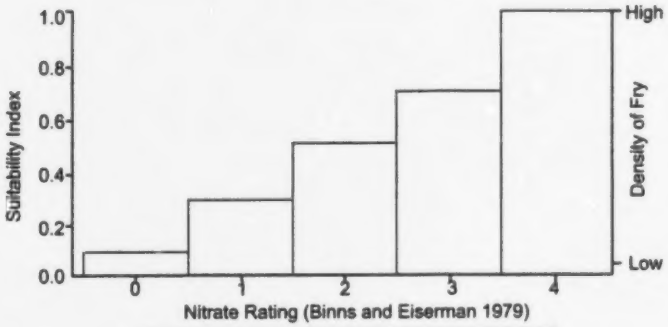


X	Y
2	0.33
100	0.80
200	1.00

* area = area of site

' time = time in period t

Terrell *et al.* 1995

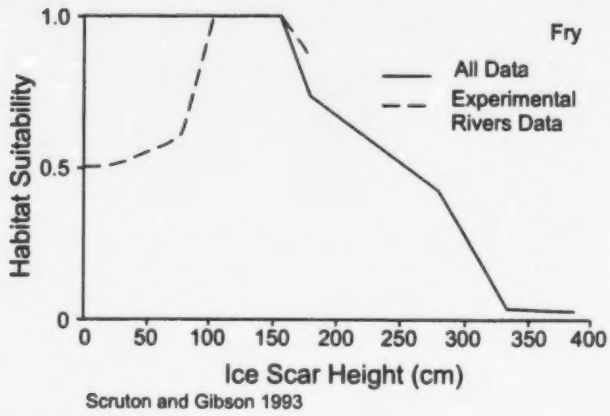


0 (worst)	1	2	3	4 (best)
<0.01 or >2.0	0.01-0.04 or 0.91-2.0	0.05-0.09 or 0.51-0.90	0.10-0.14 or 0.26-0.50	0.15-0.25

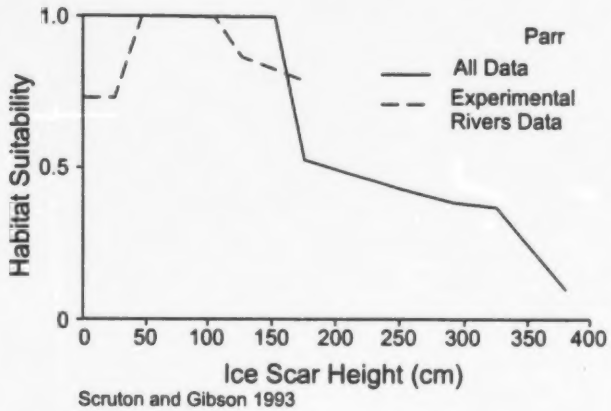
(Measurements in $mg \cdot l^{-1}$)

Terrell *et al.* 1995

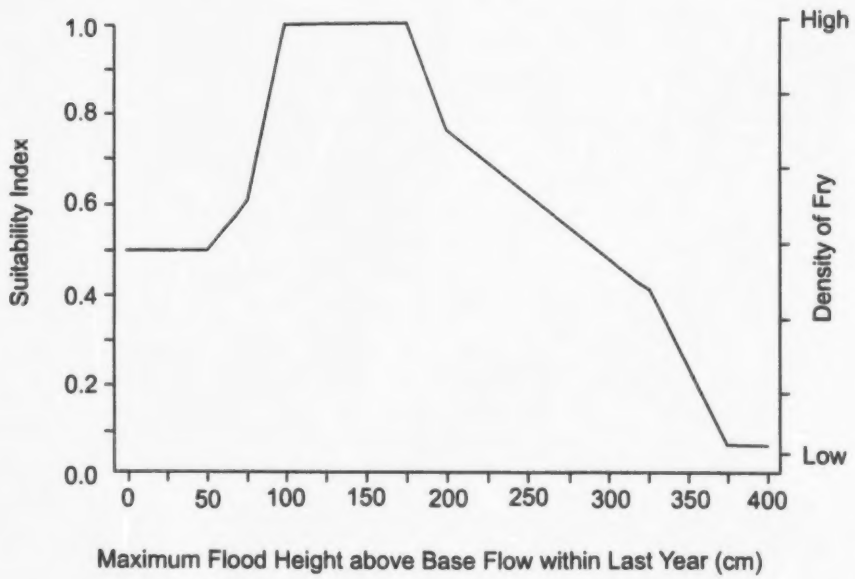
Ice scour and maximum flood height suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993



Scruton and Gibson 1993

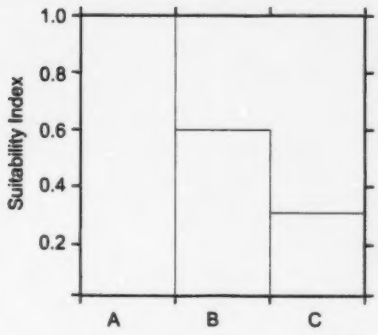


Terrell *et al.* 1995

Appendix B

Macrohabitat suitability criteria for various life stages of brook trout

Pool ratio and discharge suitability criteria for various life stages of brook trout



Pool class rating during the late growing season low flow period (Aug.-Oct.)
The rating is based on the percent of the area containing pools of the three classes described below.

A) ≥30% of the area is comprised of first-class pools.
B) ≥10% but < 30% first-class pools or ≥50% second-class pools.
C) < 10% first-class pools and < 50% second-class pools

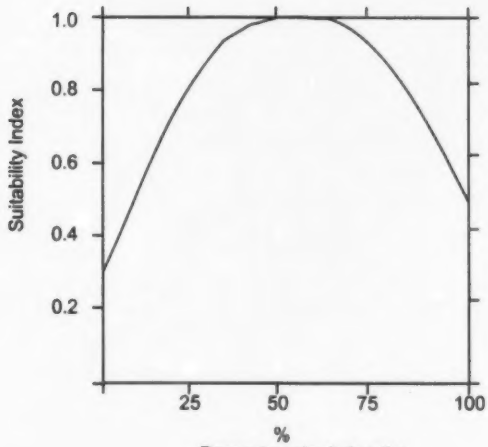
Pool class descriptions

First-class pool: Large and deep. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. More than 30% of the pool bottom is obscured due to depth, surface turbulence, or the presence of structures such as logs, debris piles, boulders, or overhanging banks and vegetation. Or, the greatest pool depth is ≥1.5 m in streams ≤5 m wide or ≥2 m deep in streams ≥5m wide.

Second-class pool: moderate size and depth. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. From 5 to 30% of the bottom is obscured due to surface turbulence, depth, or the presence of structures. Typical second-class pools are large eddies behind boulders and low velocity, moderately deep areas beneath overhanging banks and vegetation.

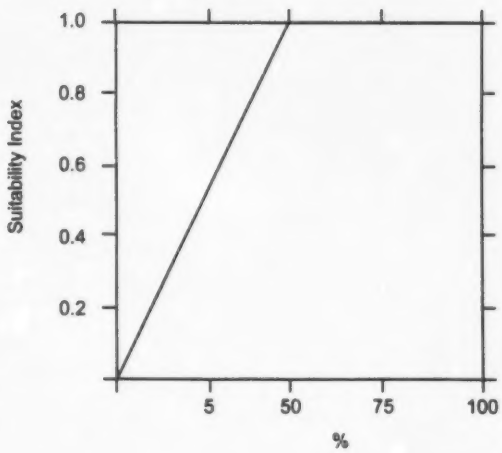
Third-class pool: Small or shallow or both. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. Cover, if present, is in the form of shade, surface turbulence, or very limited structures. Typical third-class pools are wide, shallow, reduced velocity areas of streams or small eddies behind boulders.

Raleigh 1982



Percent pools during the late growing season low water period.

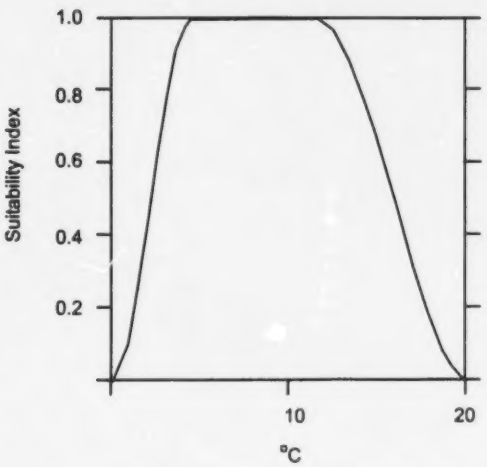
Raleigh 1982



Average annual base flow regime during the late summer or winter low flow period as a percent of the average annual daily flow.

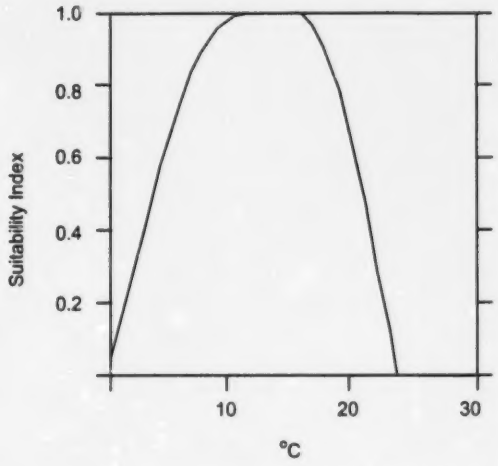
Raleigh 1982

Temperature suitability criteria for various life stages of brook trout



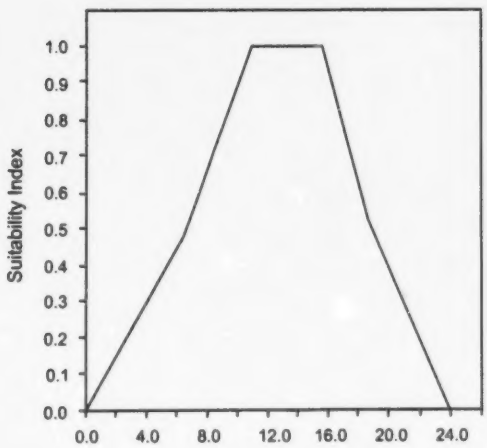
Average maximum water temperature (°C) during embryo development

Raleigh 1982



Average maximum water temperature (°C) during the warmest period of the year (adult, juvenile and fry)

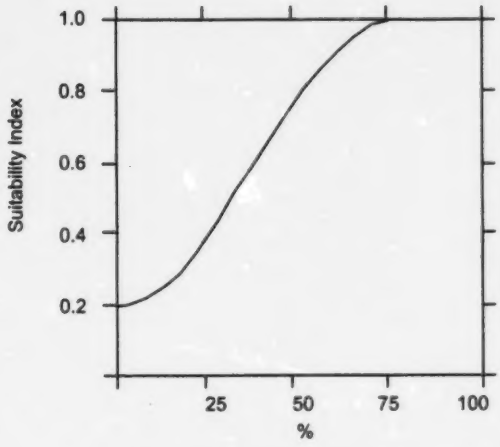
Raleigh 1982



Water temperature SI curve for juvenile brook trout developed using the Delphi method

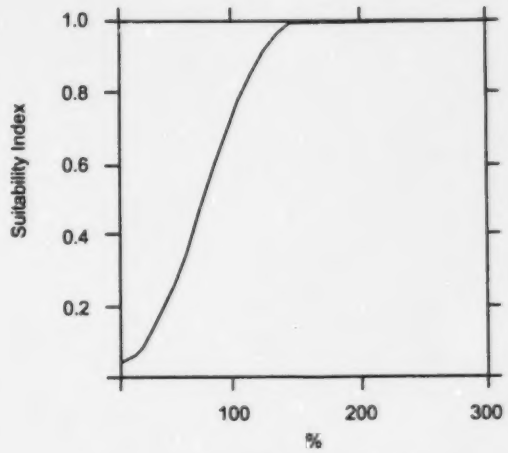
Jirka and Homa 1990

Cover suitability criteria for various life stages of brook trout



Average percent rooted vegetation and stable rocky ground cover along the streambank during the summer (erosion control).

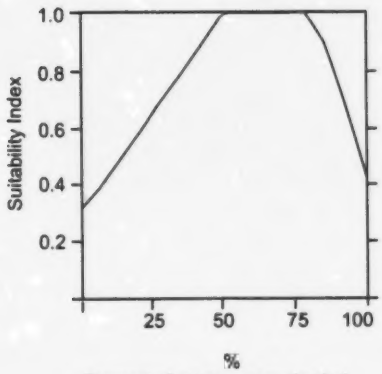
Raleigh 1982



Average percent vegetation (trees, shrubs and grasses-forbs) along the streambank during the summer for allochthonous input. Vegetation Index = 2 (% shrubs) + 1.5 (% grasses) + (% trees) + 0 (% bareground).

(For streams ≤ 50m wide)

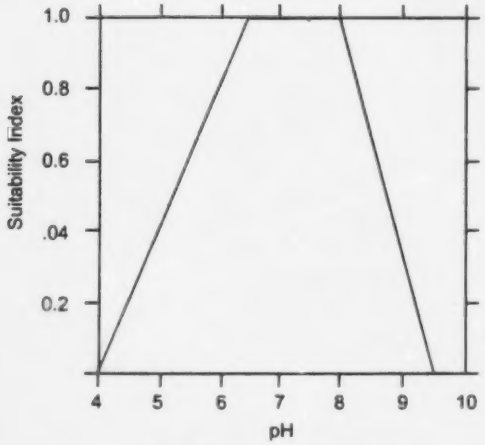
Raleigh 1982



Percent of stream area shaded between 1000 and 1400 hrs (for streams ≤ 50m wide). Do not use on cold (16 °C max. temp.), unproductive streams.

Raleigh 1982

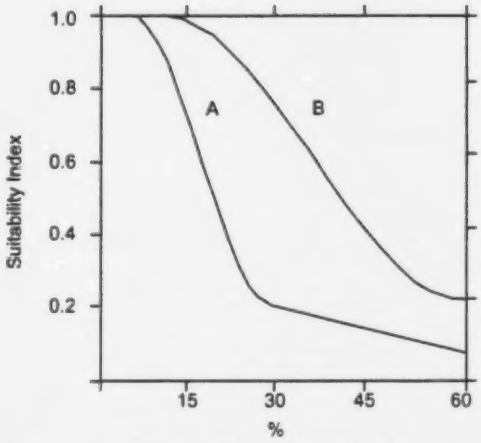
Water quality suitability criteria for various life stages of brook trout



Annual maximal or minimal pH. Use the measurement with the lowest SI value.

For lacustrine habitats, measure pH in the zone with the best combination of dissolved oxygen and temperature.

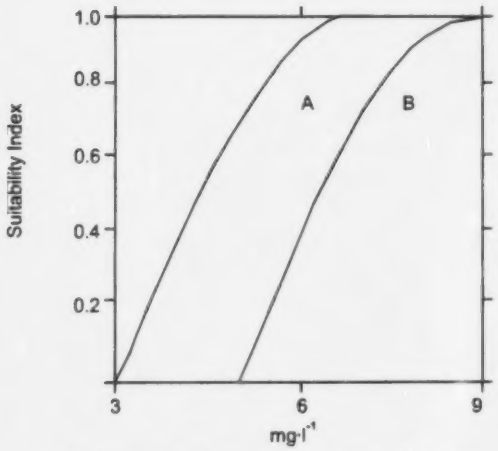
Raleigh 1982



Percent fines (< 3 mm) in riffle-run and in spawning areas during average summer flows

A = Spawning
B = Riffle-run

Raleigh 1982



Average minimum dissolved oxygen ($mg \cdot l^{-1}$) during the late growing season low water period and during embryo development (adult, juveniie,fry, and embryo).

For lacustrine habitats, use the dissolved oxygen readings in temperature zones nearest to optimum where dissolved oxygen is > 3 $mg \cdot l^{-1}$.

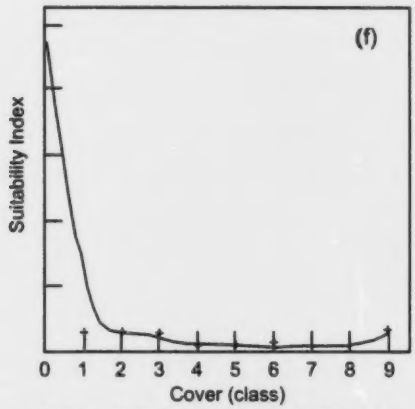
A = < 15 °C
B = ≥ 15 °C

Raleigh 1982

Appendix C

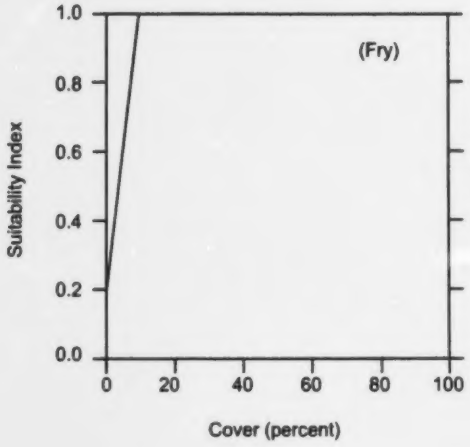
Macrohabitat suitability criteria for various life stages of brown trout

Cover suitability criteria for various life stages of brown trout

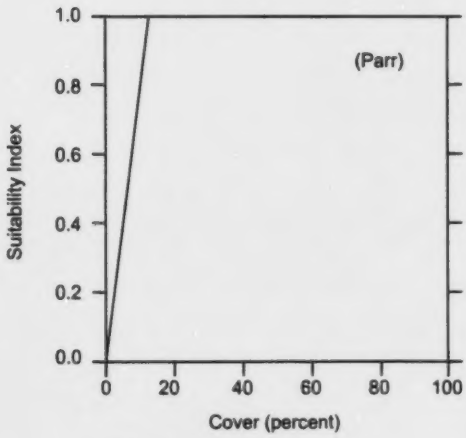


Habitat suitability curves, based on habitat use for brown trout (+) parr in the R. Gjengedalselva, 1987-88. (f) Cover.

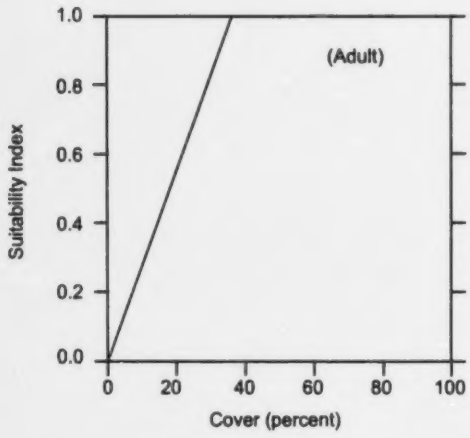
Heggenes and Saltveit 1990



Raleigh *et al.* 1986

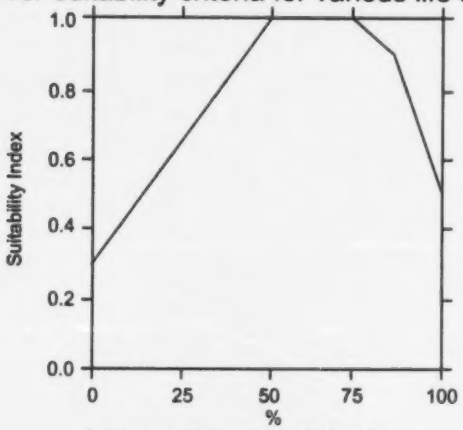


Raleigh *et al.* 1986



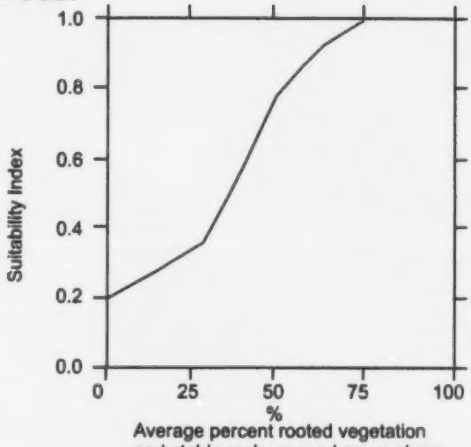
Raleigh *et al.* 1986

Cover suitability criteria for various life stages of brown trout



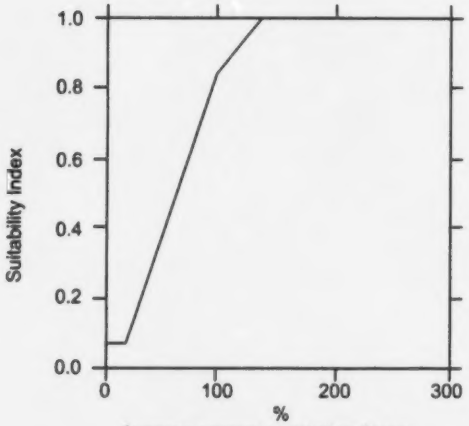
Percent of stream area shaded between 1000 and 1400 hrs (for streams ≤ 50m wide). Do not use for cold (≤18 °C), unproductive streams

Raleigh *et al.* 1986



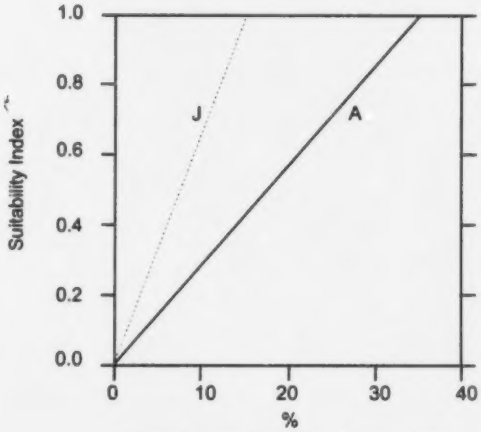
Average percent rooted vegetation and stable rocky ground cover along the streambank during the summer (erosion control).

Raleigh *et al.* 1986



Average percent vegetation (trees, shrubs and grasses-forbs) along the streambank during the summer for allochthonous input. Vegetation Index = 2 (%shrubs) + 1.5 (%grasses) + (%trees) + 0 (% bare ground). (For unproductive streams ≤ 15m wide)

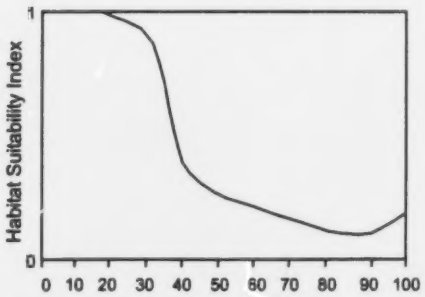
Raleigh *et al.* 1986



Percent cover during the late growing season, low-water period at depths >15 cm and near bottom velocities ≤15 cm per second.

J = juveniles
A = adults

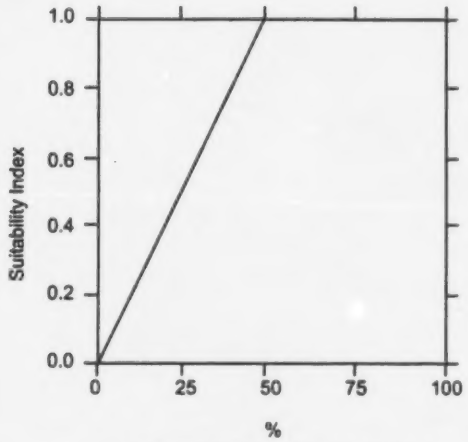
Raleigh *et al.* 1986



Habitat suitability index curve for cover use by brown trout in small streams

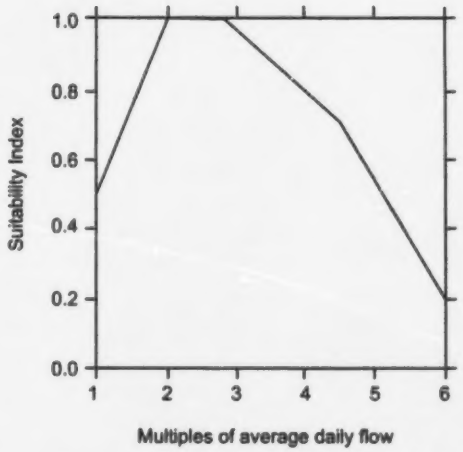
Høggenes 1994

Discharge suitability criteria for various life stages of brown trout



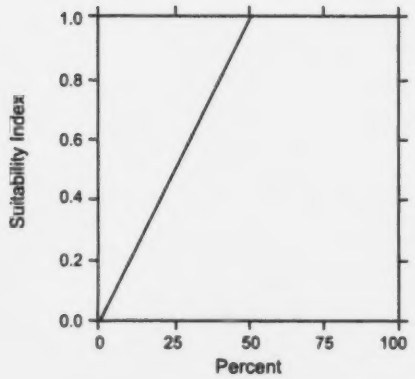
Average annual base flow regime during the late summer or winter low-flow period as a percentage of the average annual daily flow (cfs).

Raleigh *et al.* 1986



Average annual peak flow as a multiple of the average annual daily flow. For embryo and fry habitat suitability, use the average and highest flows that occur from time of egg deposition until two weeks after fry emergence.

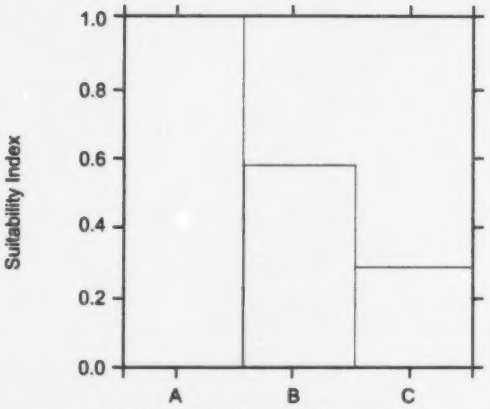
Raleigh *et al.* 1986



Suitability index graph for the average annual base flow regime (v_{ss}) during the late-summer and winter low-flow period as a percentage of the average annual daily flow (Raleigh *et al.* 1986).

Wesche *et al.* 1987a

Pool ratio and rating suitability criteria for various life stages of brown trout



Pool class rating during the late growing season low flow period.
The rating is based on the percent of the area containing pools of the three classes described below.

A) ≥ 30% of the area is comprised of first-class pools.
B) ≥10% but < 30% first-class pools or ≥50% second-class pools.
C) < 10% first-class pools and < 50% second-class pools

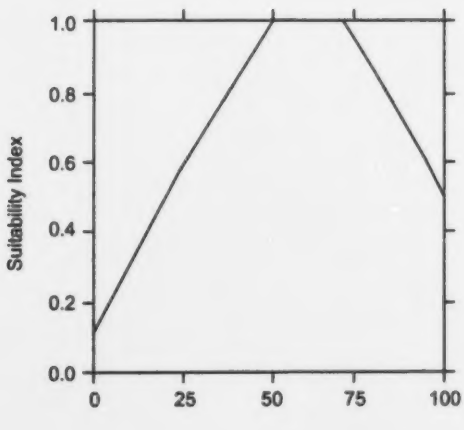
Raleigh *et al.* 1986

Pool class descriptions

First-class pool: Large and deep. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. More than 30% of the pool bottom is obscured due to depth, surface turbulence, or the presence of structures such as logs, debris piles, boulders, or overhanging banks and vegetation. Or, the greatest pool depth is ≥1.5 m in streams ≤5 m wide or ≥2 m deep in streams >5m wide.

Second-class pool: moderate size and depth. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. From 5% to 30% of the bottom is obscured due to surface turbulence, depth, or the presence of structures. Typical second-class pools are large eddies behind boulders and low velocity, moderately deep areas beneath overhanging banks and vegetation.

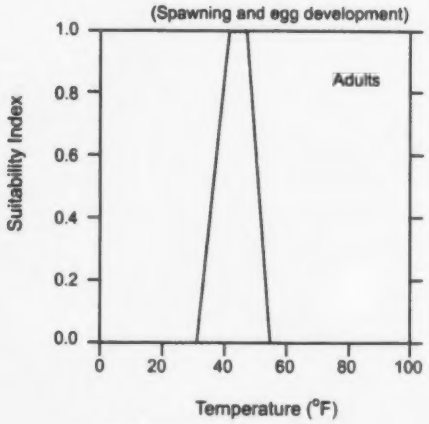
Third-class pool: Small or shallow or both. Pool depth and size are sufficient to provide a low velocity resting area for adult trout. Cover, if present, is in the form of shade, surface turbulence, or very limited structures. Typical third-class pools are wide, shallow, reduced velocity areas of streams or small eddies behind boulders. Virtually the entire bottom area of the pool is discernible.



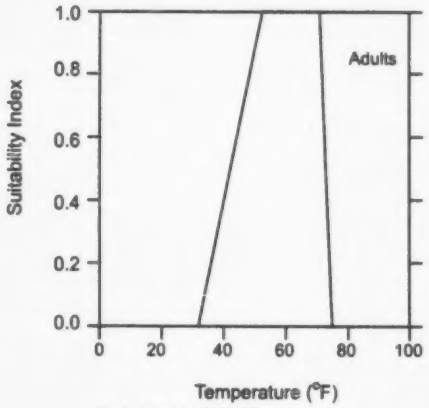
Percent pools during the late growing season, low-water period.

Raleigh *et al.* 1986

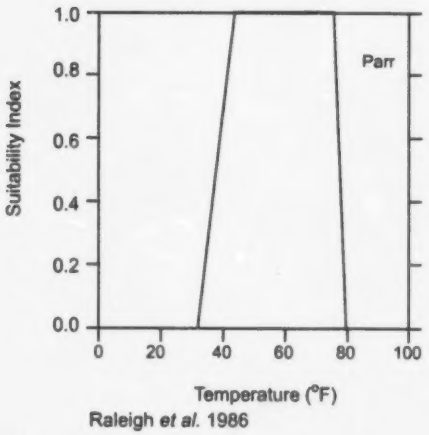
Temperature suitability criteria for various life stages of brown trout



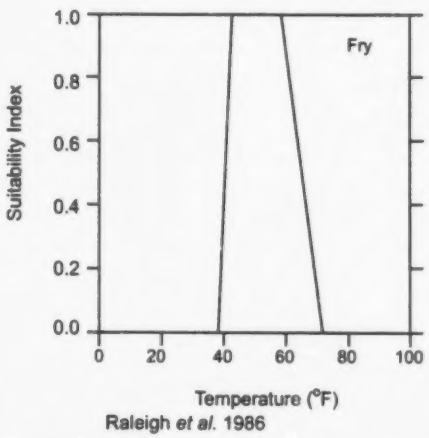
Raleigh *et al.* 1986



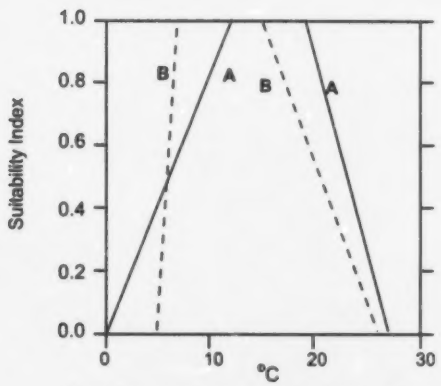
Raleigh *et al.* 1986



Raleigh *et al.* 1986

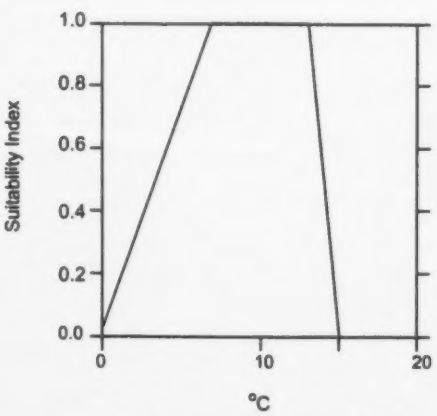


Raleigh *et al.* 1986



Maximum water temperature (°C) during the warmest period of the year (adult, juvenile, and fry).
For lacustrine habitats, use the temperature strata nearest to optimum in dissolved oxygen zones >3 mg·l^{-1}.

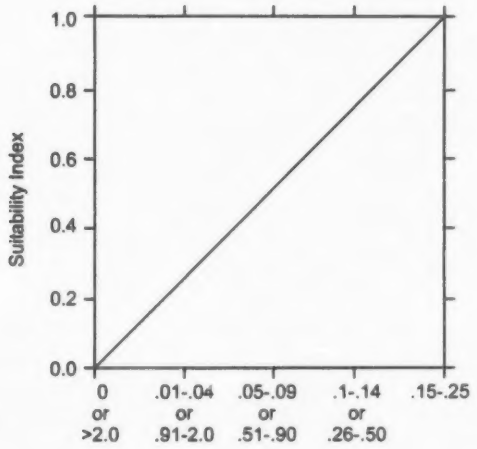
Raleigh *et al.* 1986



Maximum water temperature (°C) during embryo development

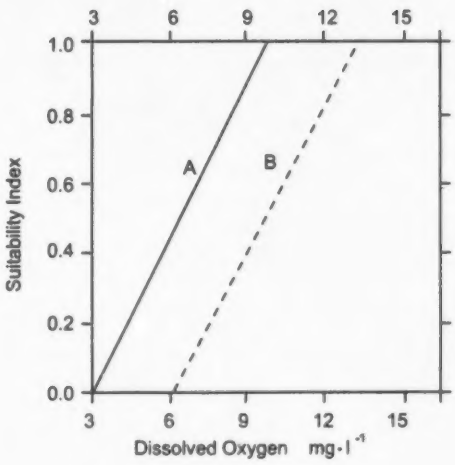
Raleigh *et al.* 1986

Water Quality suitability criteria for various life stages of brown trout



Levels of late summer nitrate-nitrogen

Raleigh *et al.* 1986

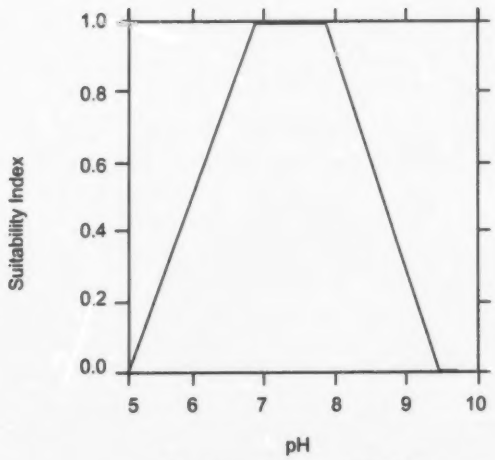


Minimum dissolved oxygen ($mg \cdot l^{-1}$) during the late growing season, low-water period and during embryo development (adult, juvenile, fry and embryo).

For lacustrine habitats, use the dissolved oxygen readings in temperature zones nearest to optimum where dissolved oxygen is > 3 $mg \cdot l^{-1}$

A = ≤10 °C
B = >10 °C

Raleigh *et al.* 1986



Annual maximal or minimal pH. Use the measurement with the lowest SI.

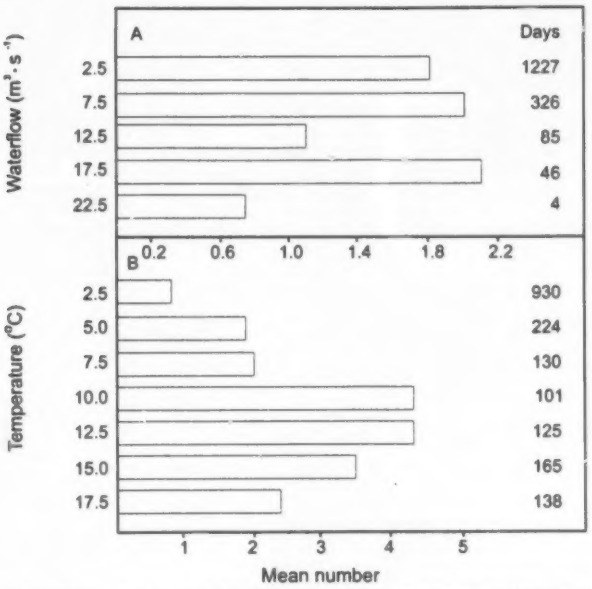
Raleigh *et al.* 1986

Appendix D

Macrohabitat suitability criteria for various life stages of Arctic charr

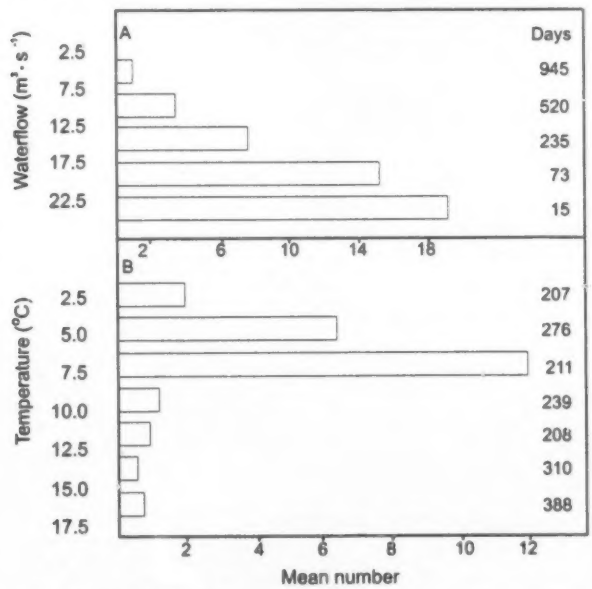
Macrohabitat relationships for Arctic charr

Note: This data was not converted into final Habitat Suitability Indices



Mean number of descending Arctic charr per day at water-flows between O-4.99 (2.5), 5.00-9.99 (7.5), 10.00-14.99 (12.5) $m^3 \cdot s^{-1}$ etc. during 1 January - 30 June 1976 - 1985 in the River Imsa.
B. Mean number of descending Arctic charr per day at temperatures between O-3.74 (2.5), 3.75-6.24 (5.0), 6.25-8.74 (7.5) °C etc. during 1 January - 30 June 1976-1985 in the River imsa.

Jensen *et al.* 1989

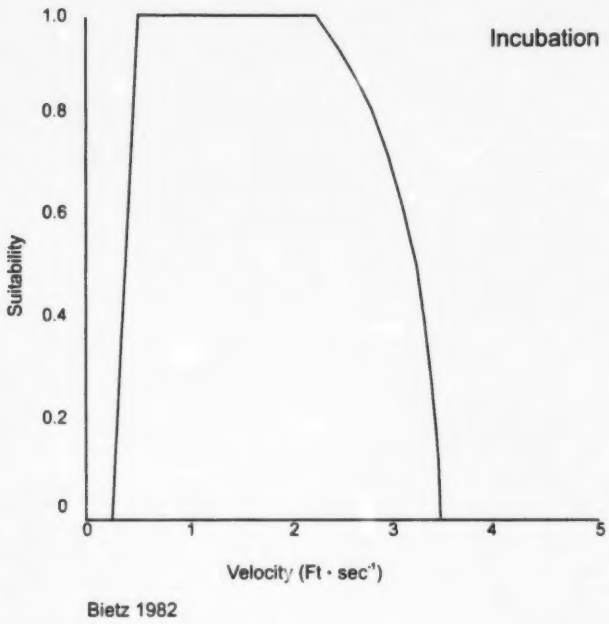


Mean number of descending Arctic charr per day at water-flows between 0-4.99 (2.5), 5.00-9.99 (7.5), 10.00-14.99 (12.5) $m^3 \cdot s^{-1}$ etc. during 1 July - 31 December 1976 - 1985 in the River Imsa.
B. Mean number of descending Arctic charr per day at temperatures between 0-3.74 (2.5), 3.75-6.24 (5.0), 6.25-8.74 (7.5) °C etc. during 1 July - 31 December 1976-1985 in the River Imsa.
Jensen *et al.* 1989

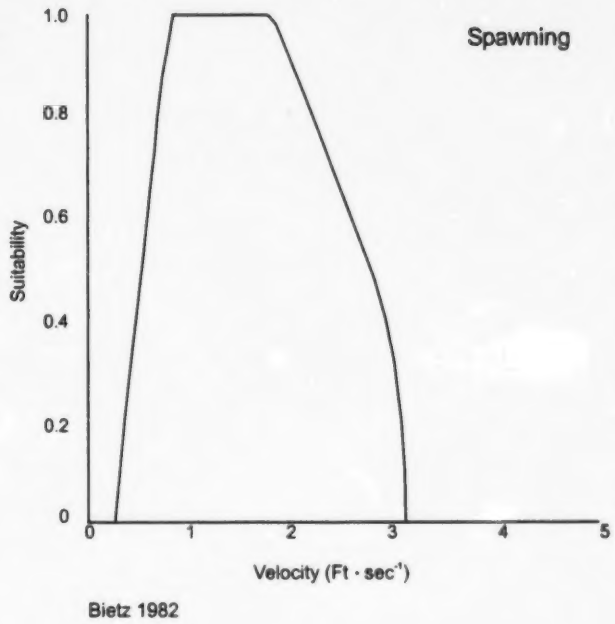
Appendix E

Microhabitat suitability criteria for various life stages of Atlantic salmon

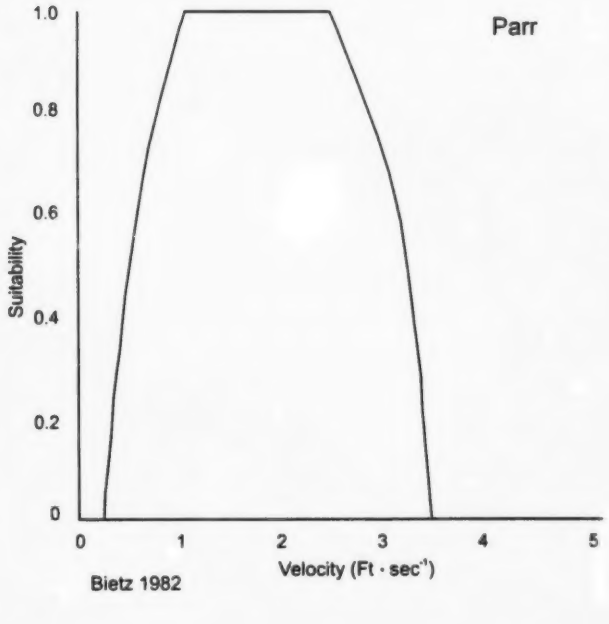
Velocity suitability criteria for various life stages of Atlantic salmon



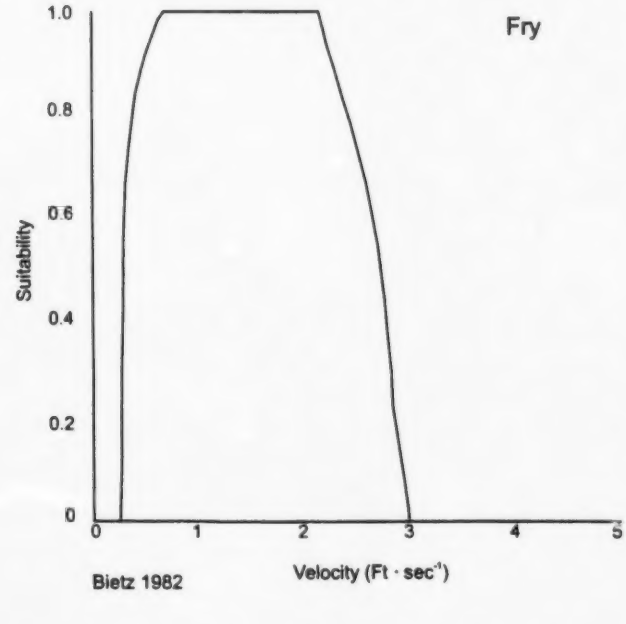
Bietz 1982



Bietz 1982

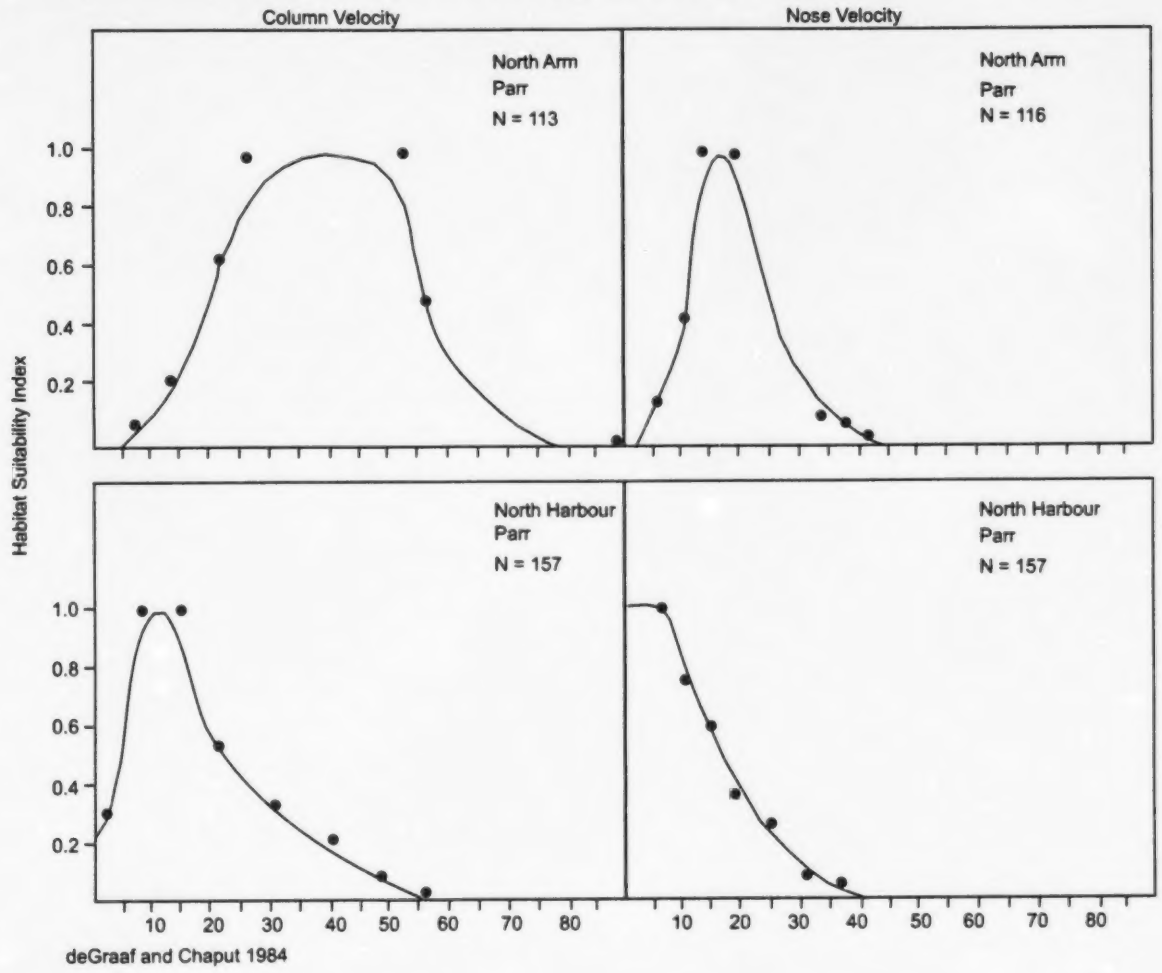


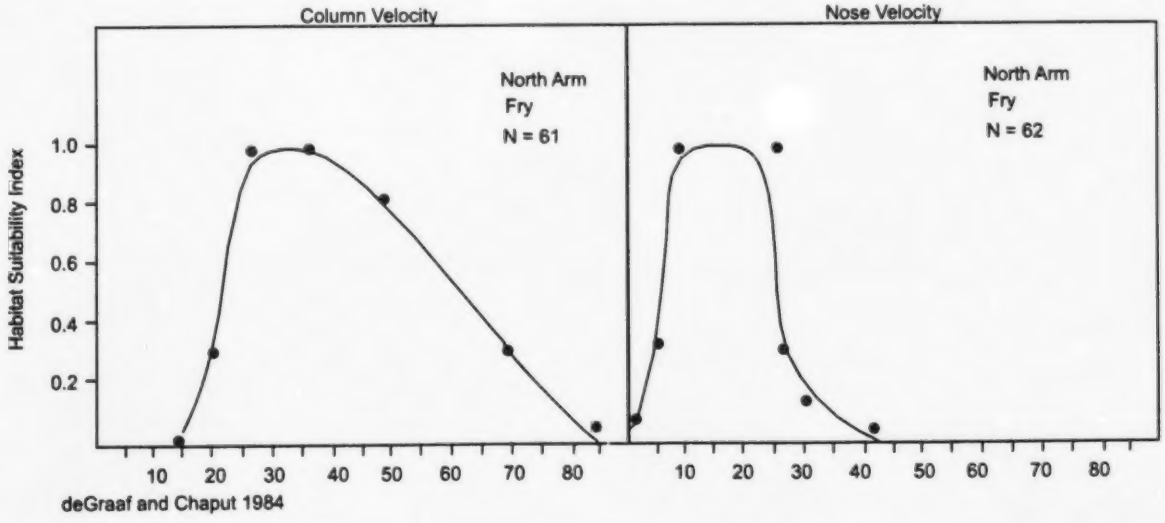
Bietz 1982



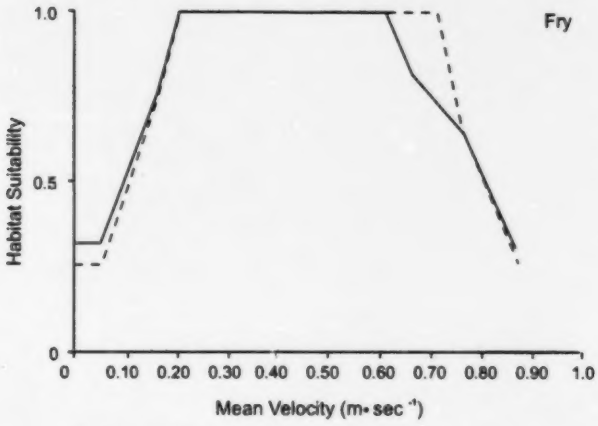
Bietz 1982

Velocity suitability criteria for various life stages of Atlantic salmon

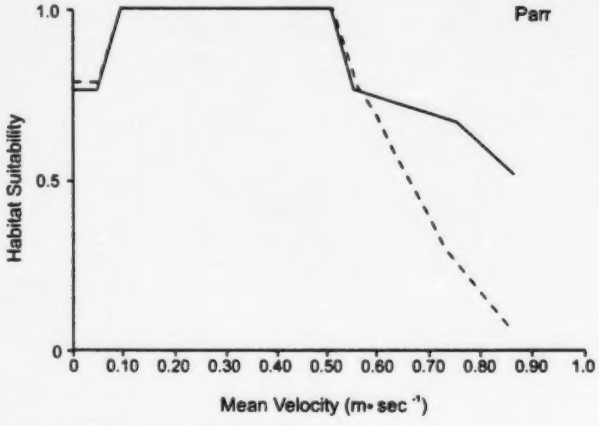




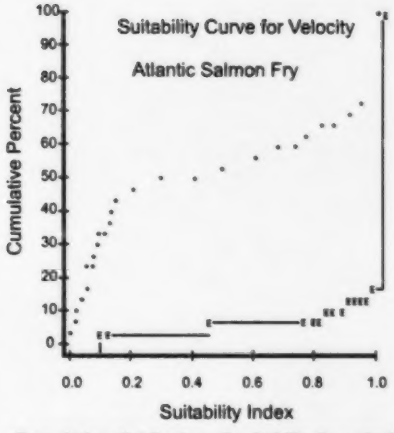
Velocity suitability criteria for various life stages of Atlantic salmon



Scruton and Gibson 1993

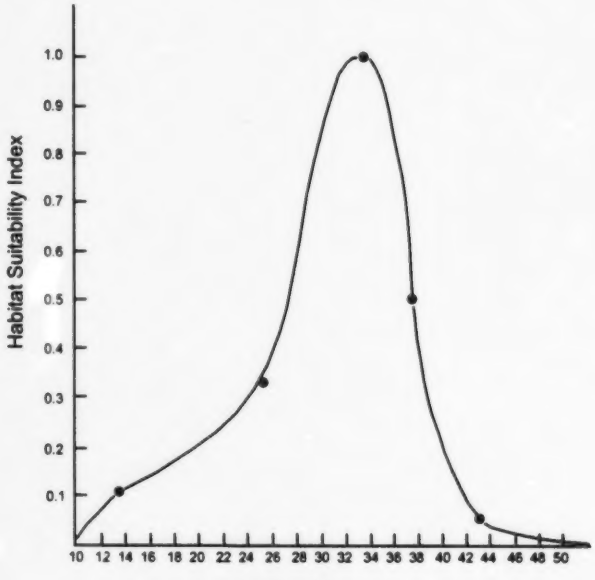


Scruton and Gibson 1993



Cumulative distribution of suitability for velocities used by Atlantic salmon fry in Maine streams (E) and for the points on the velocity suitability curve (*) in Trial and Stanley (1984).

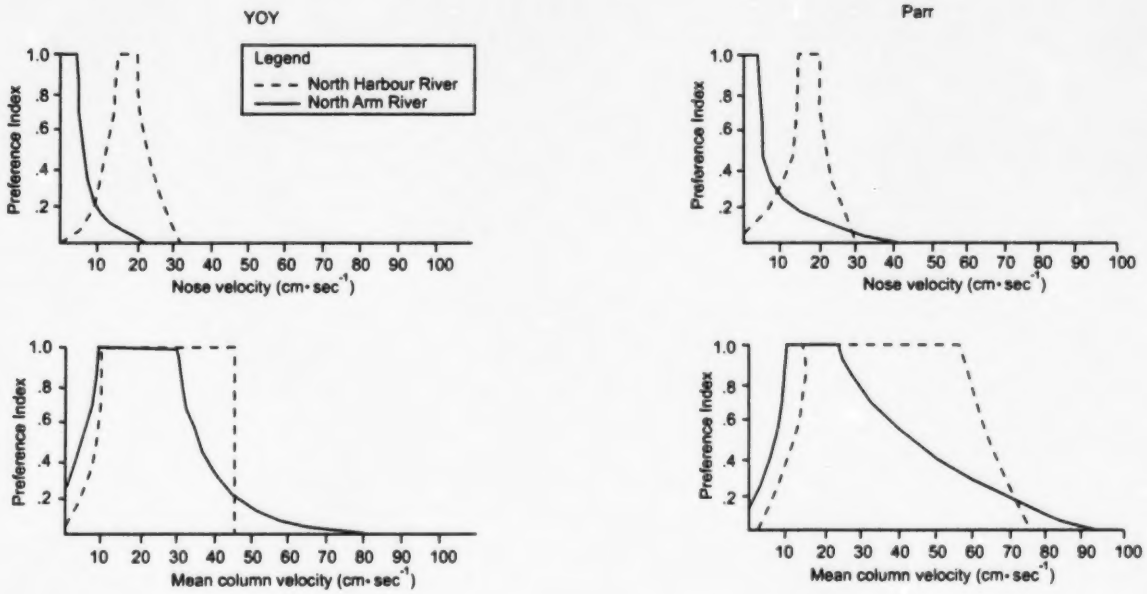
Trial 1989



Column velocity habitat utilization curve for spawning Atlantic salmon, based upon results from Northeast River tributary.

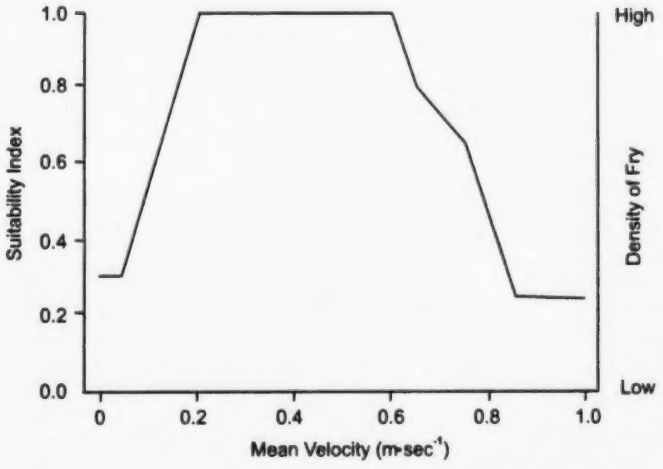
deGraaf and Chaput 1984

Velocity suitability criteria for various life stages of Atlantic salmon



Habitat-preference curves for Atlantic salmon YOY and parr in type-A (North Arm River) and type-B (North Harbour River) habitats in Newfoundland

deGraaf and Bain 1986

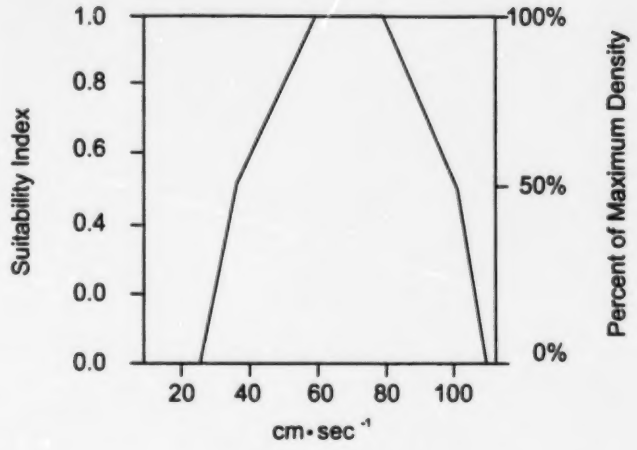


Terrel *et al.* 1995

Velocity suitability criteria for various life stages of Atlantic salmon

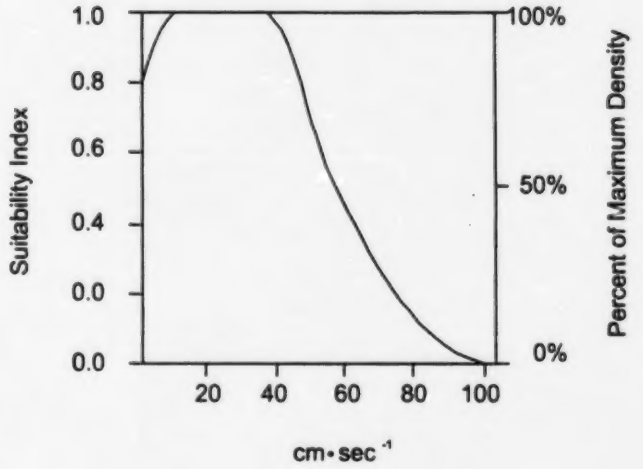
Mean column velocity for reproduction, measured at the bottom 60% of depth

Stanley and Trial 1992



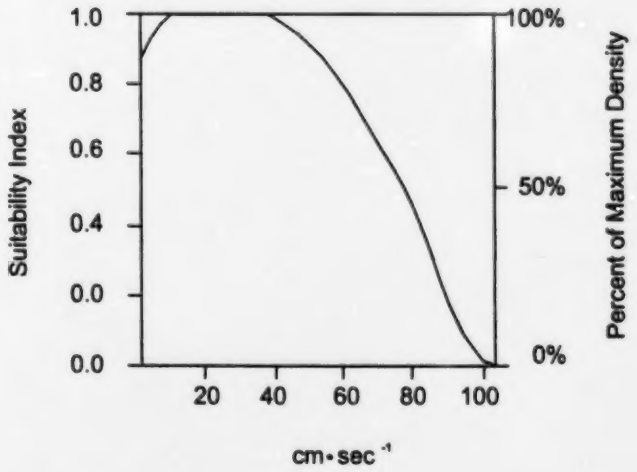
Mean column velocity for fry, measured for the bottom 60% of depth

Stanley and Trial 1992

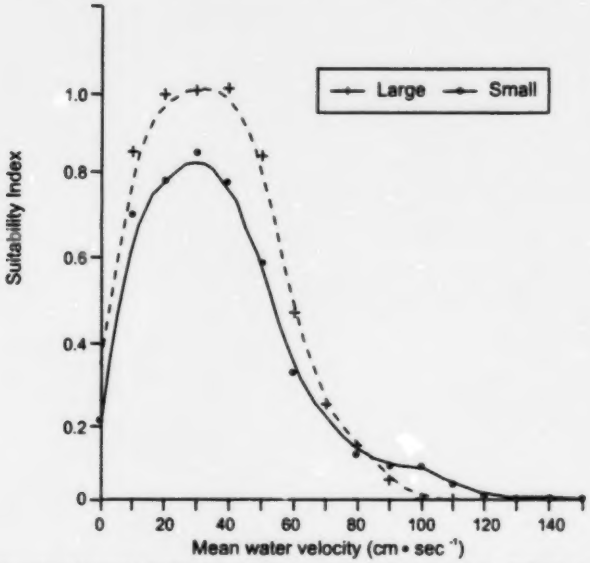


Mean column velocity for parr measured for the bottom 60% of depth

Stanley and Trial 1992

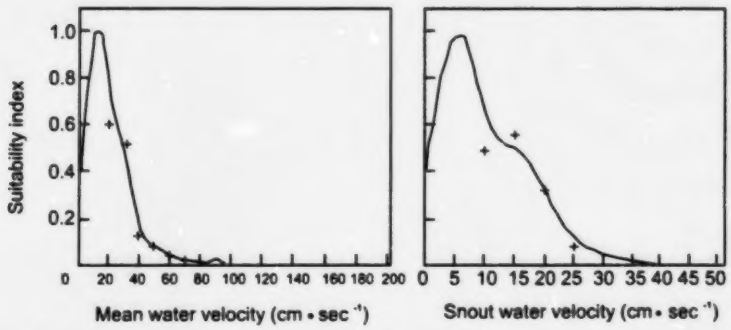


Velocity suitability criteria for various life stages of Atlantic salmon

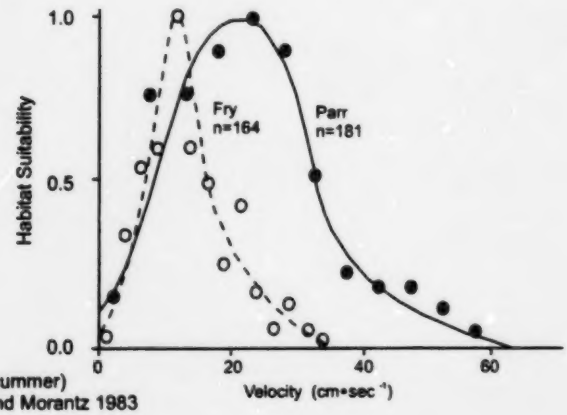


Generalized habitat suitability curve for use of mean water velocities for Atlantic salmon parr (solid line) and young of the year (dotted line), based on several published studies. (Curve calculated by the author).

Heggenes 1990

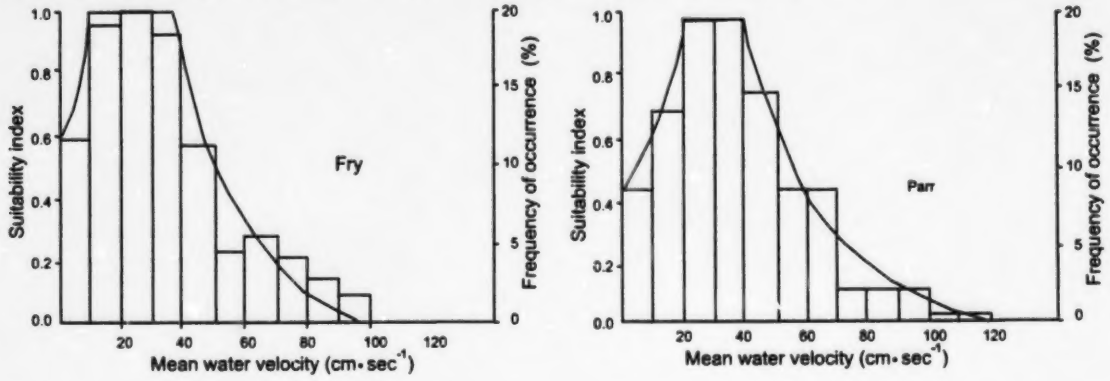

Suitability index
1.0
0.8
0.6
0.4
0.2
0 20 40 60 80 100 120 140 160 180 200
Mean water velocity (cm • sec -1)
0 5 10 15 20 25 30 35 40 45 50
Snout water velocity (cm • sec -1)

Heggenes and Saltveit 1990 Atlantic salmon parr (+)



(during summer)
Shirvall and Morantz 1983

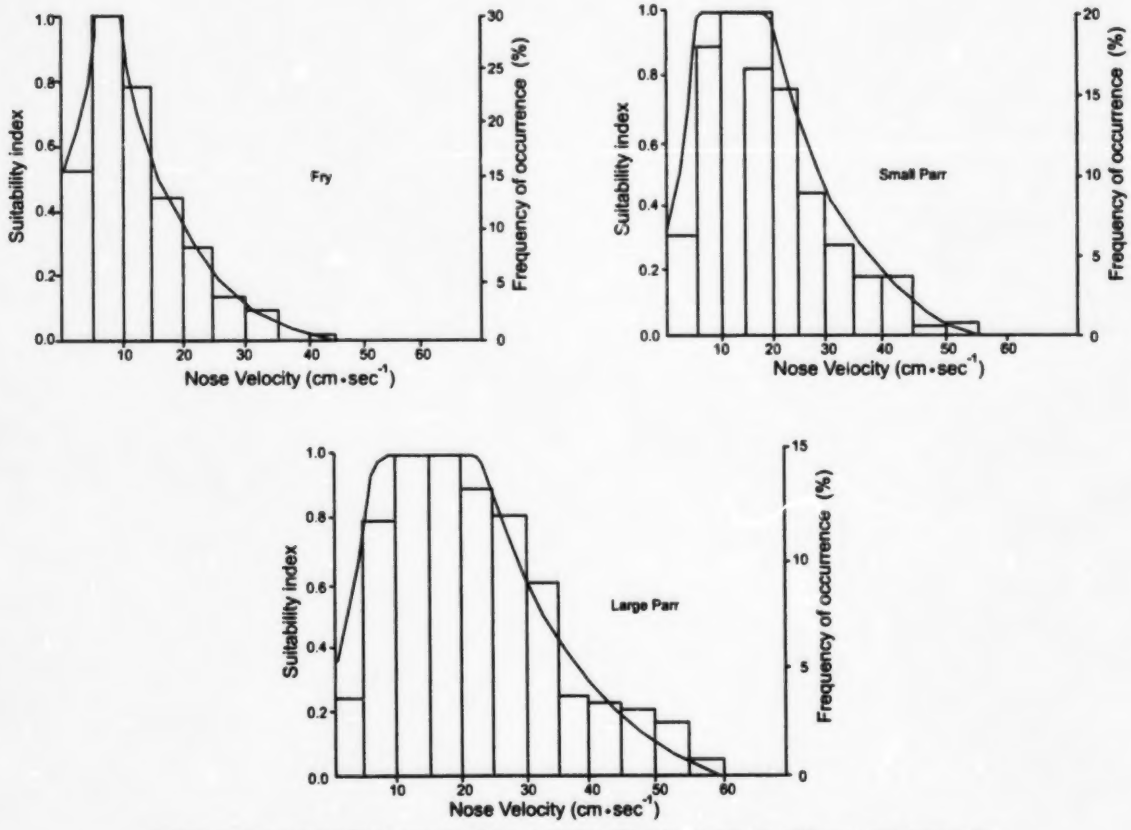
Velocity suitability criteria for various life stages of Atlantic salmon



Mean water velocity (measured at 0.6 of the depth from the water surface) selection by Atlantic salmon fry and parr in six Nova Scotia and New Brunswick rivers in 1982-1984.

Bars represent frequency of occurrence; curves indicate the suitability index.

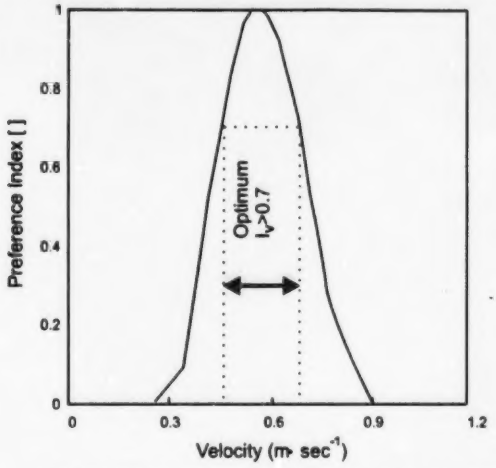
Morantz *et al.* 1987



Water velocities at the fish's nose position selected by Atlantic salmon fry, (<65mm), and large parr (>100mm) in six Nova Scotia and New Brunswick rivers in 1982-1984.
Bars represent frequency of occurrence; curves indicate the suitability index.

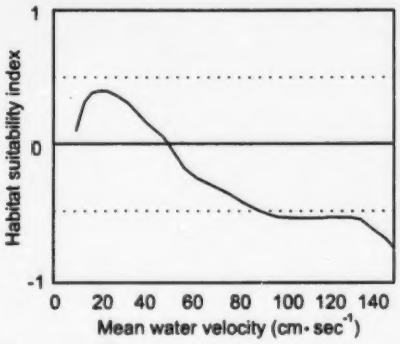
Morantz *et al.* 1987

Velocity suitability criteria for various life stages of Atlantic salmon



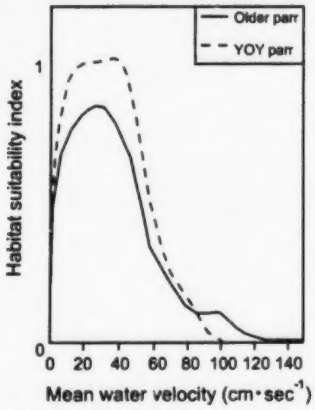
Preference curves for velocity and depth for landlocked salmon in Ashuapmushuan River.

Leclerc *et al.* 1994



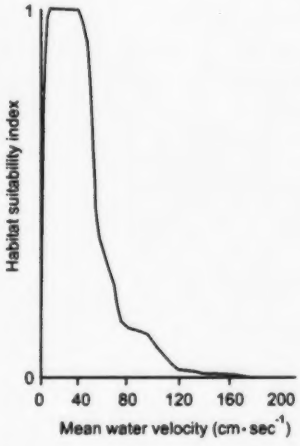
Habitat preference curve for velocty, based on usage and availability, for young Atlantic salmon in the R. Gjengedselva; (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



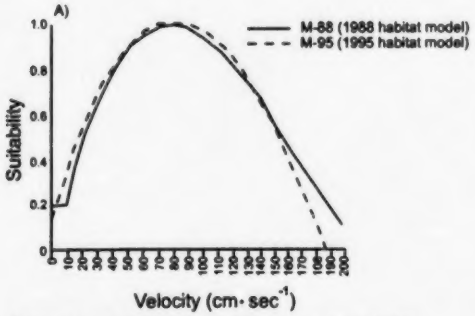
Habitat suitability curve for use of mean water velocities by young Atlantic salmon in streams. Parr avoid stillwater and are tolerant towards high water velocities (modified after Heggenes 1990)

Heggenes 1994



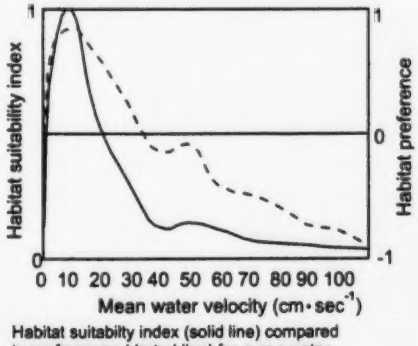
Habitat suitability index curves for velocity, based on habitat use,for young Atlantic salmon in the R. Gjengedselva; (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



Salmon parr Habitat Suitability Index for velocity. This curve applies to large rivers.

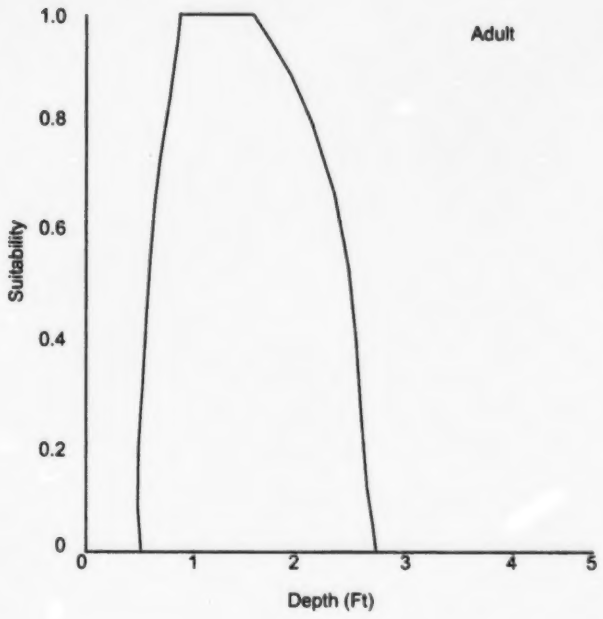
Boudreau *et al.* 1994



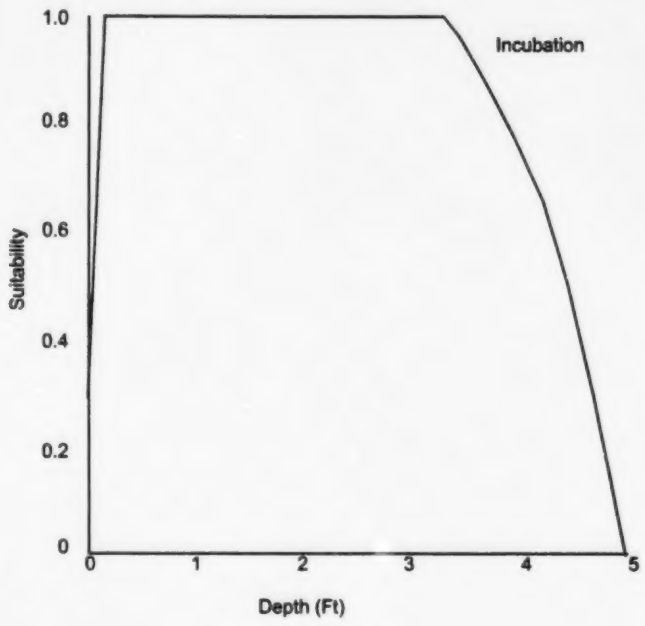
Habitat suitabilty index (solid line) compared to preferences (darted line) for mean water velocity for Atlantic salmon parr in a large Norwegian river.

Heggenes 1994

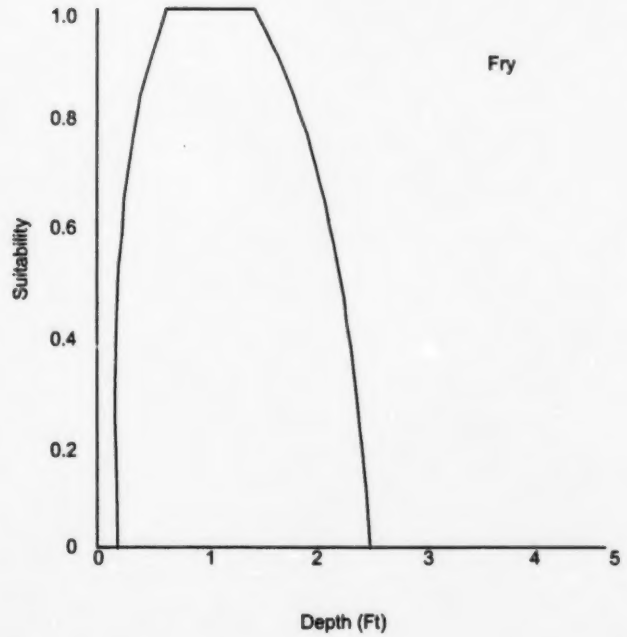
Depth suitability criteria for various life stages of Atlantic salmon



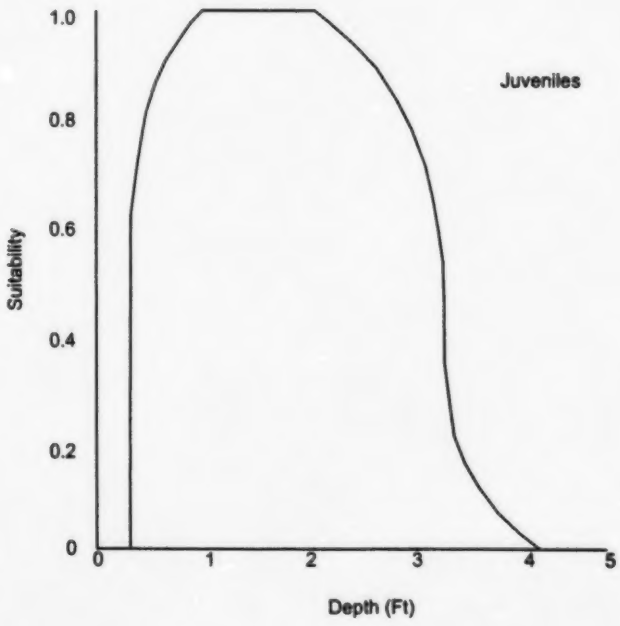
Bietz 1982



Bietz 1982

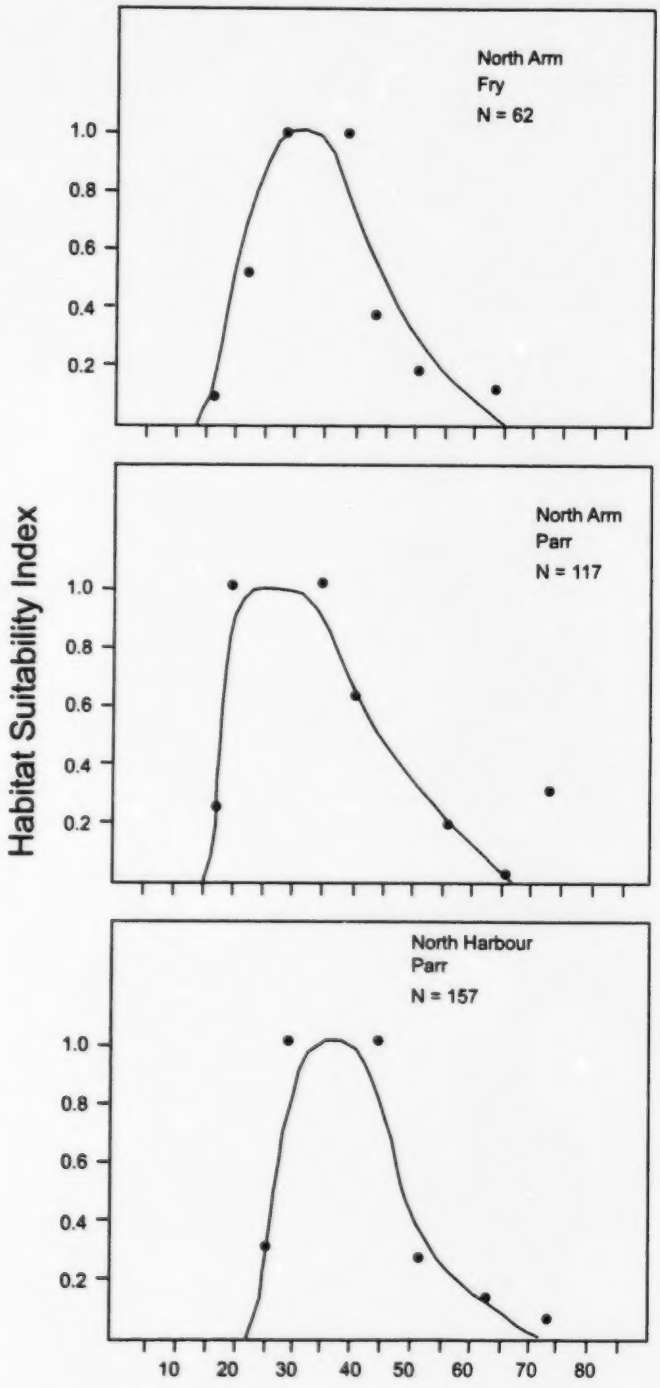


Bietz 1982



Bietz 1982

Depth suitability criteria for various life stages of Atlantic salmon

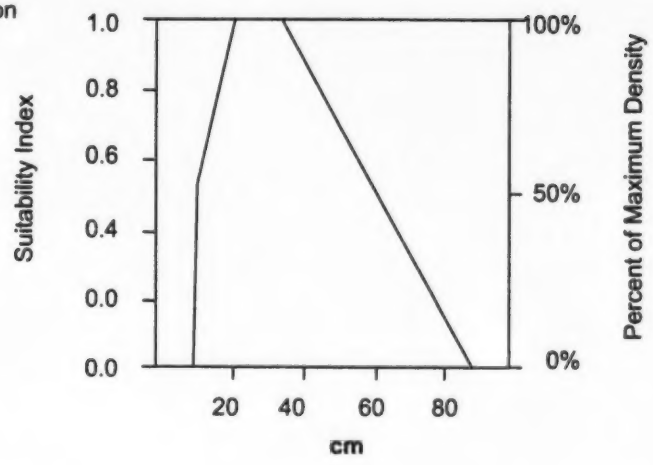


Atlantic salmon fry and parr microhabitat utilization curves for depth

deGraaf and Chaput 1984

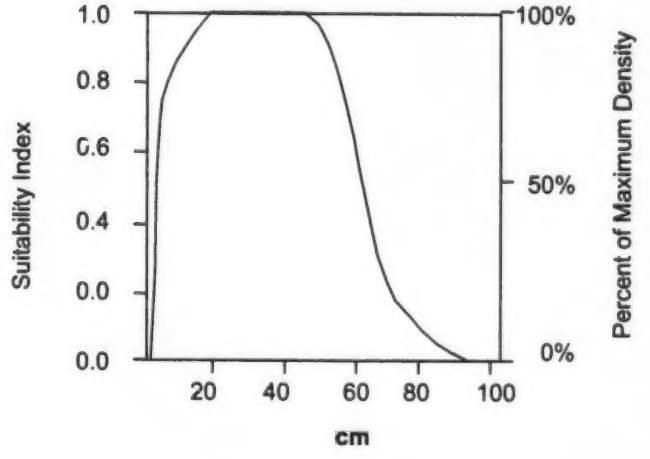
Depth suitability criteria for various life stages of Atlantic salmon

Mean depth for reproduction



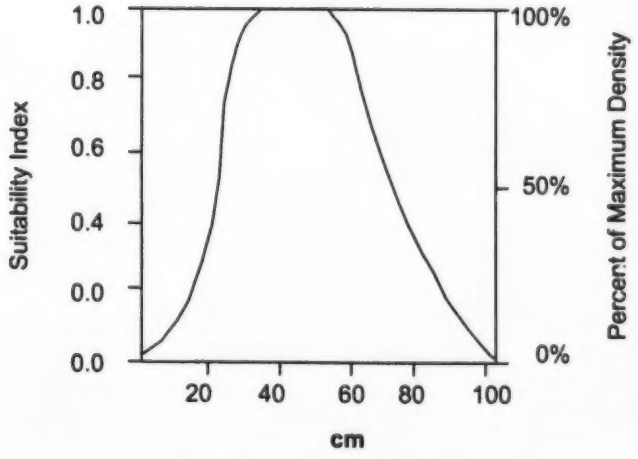
Stanley and Trial 1992

Mean depth for fry



Stanley and Trial 1992

Mean depth for parr

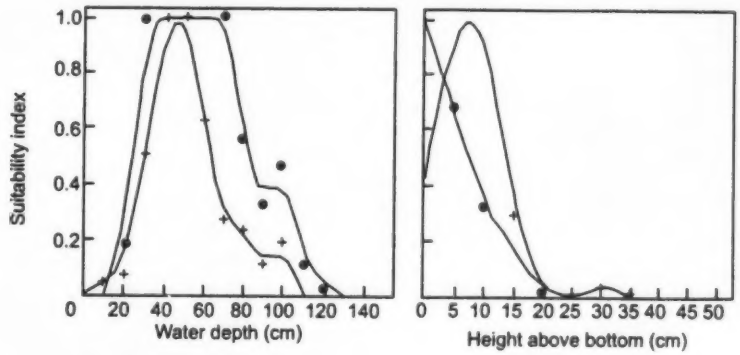


Stanley and Trial 1992

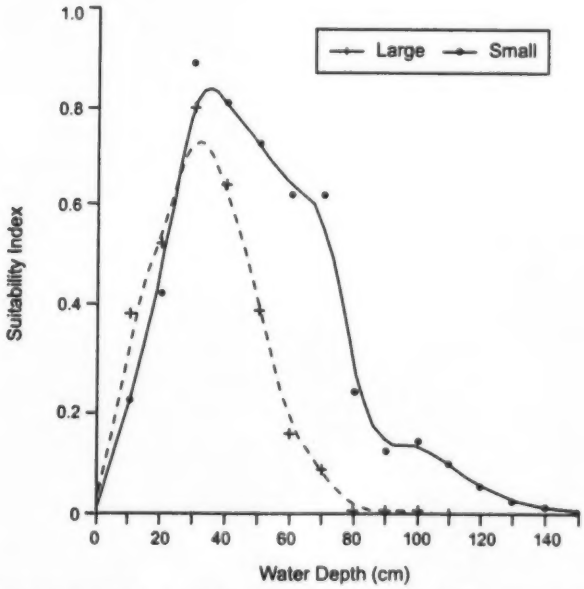
Depth suitability criteria for various life stages of Atlantic salmon

Habitat-preference curves for Atlantic salmon YOY and parr in type-A (North Arm River) and type-B (North Harbour River) habitats in Newfoundland

deGraaf and Bain 1986



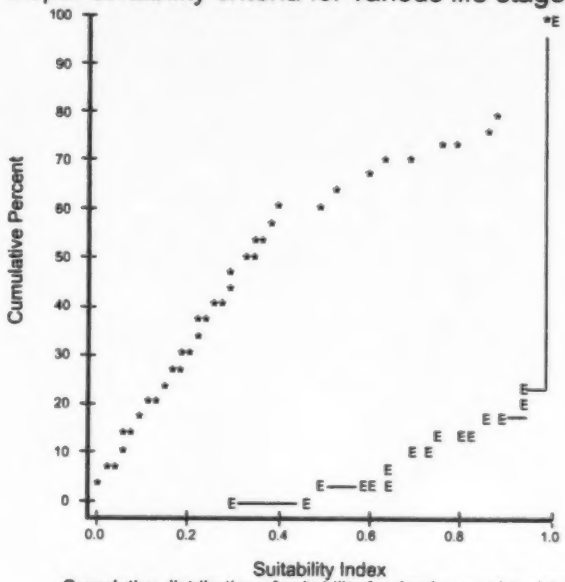
Heggenes and Saltveit 1990



Generalized habitat suitability curve for use of water depths by large Atlantic salmon parr (solid line) and small parr (young of the year) (dotted line), based on several published studies. (Curve calculated by the author).

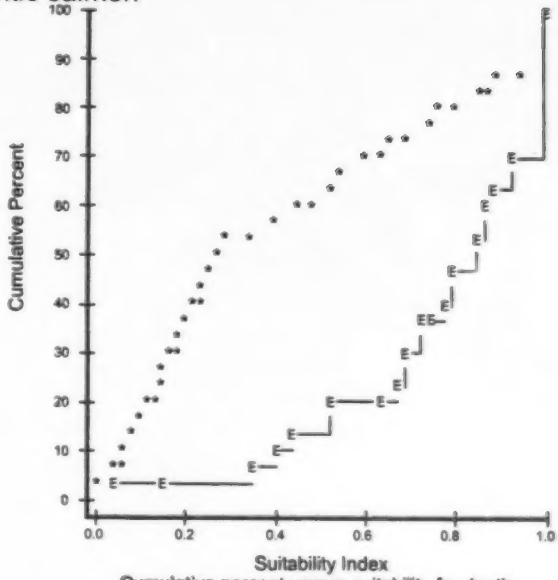
Heggenes 1990

Depth suitability criteria for various life stages of Atlantic salmon



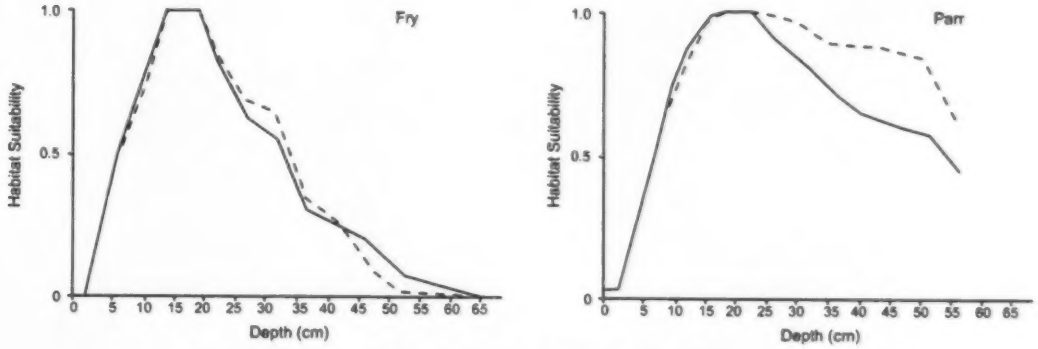
Cumulative distribution of suitability for depths used by Atlantic salmon fry in Maine streams (E) and for the points on the suitability curve for depth (*) in Trial and Stanley (1984).

Trial 1989



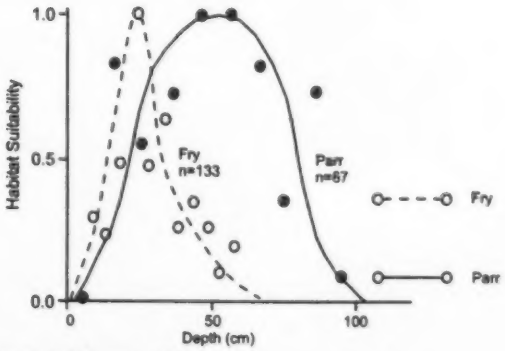
Cumulative percent versus suitability for depths used by parr in Maine streams (E) and for the points on the depth suitability curve for parr (*) in Trial and Stanley (1984).

Trial 1989

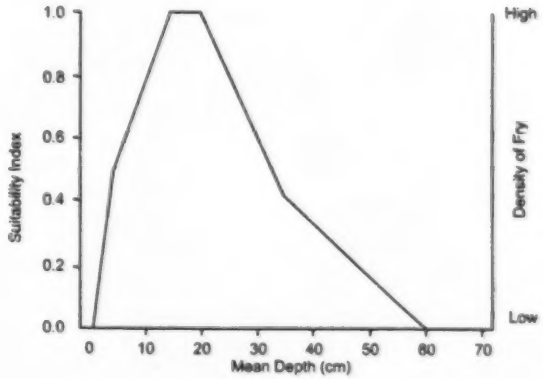


Habitat suitability curves for Atlantic Salmon fry and parr in relation to stream width and mean depth

Scruton and Gibson 1993

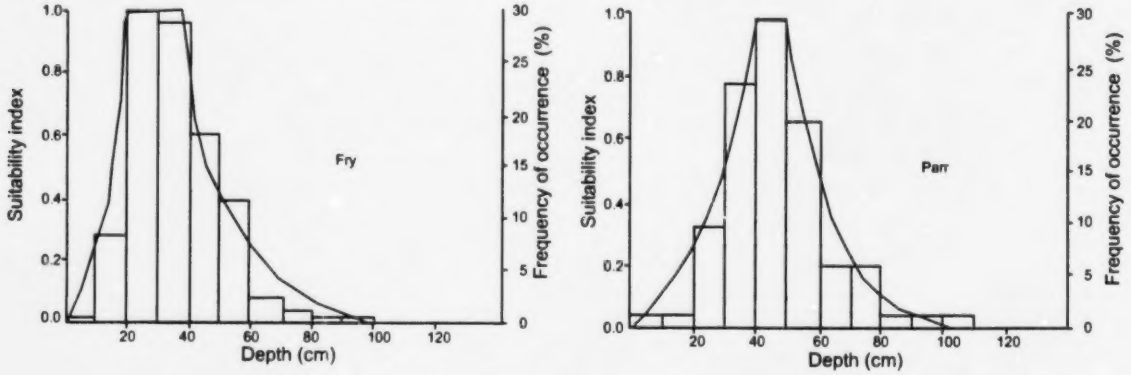


Shirvall and Morantz 1983



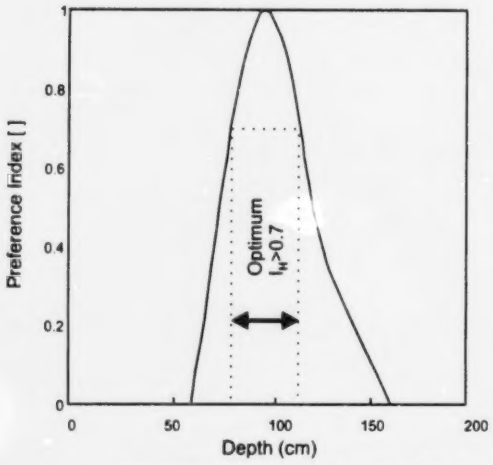
Terrel *et al.* 1995

Depth suitability criteria for various life stages of Atlantic salmon



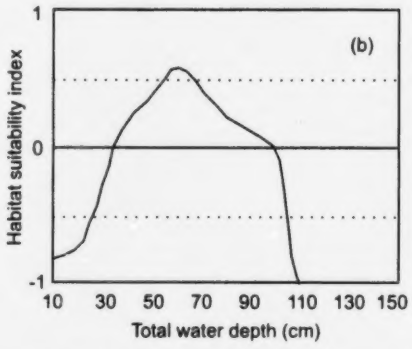
Water depth, selection by Atlantic salmon fry and parr in six Nova Scotia and New Brunswick rivers in 1982-1984. Bars represent frequency of occurrence; curves indicate the suitability index.

Morantz *et al.* 1987



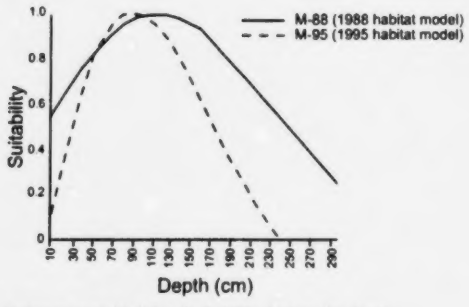
Preference curves for depth for landlocked salmon in Ashuapmushuan River.

Leclerc *et al.* 1994



Habitat preference curves for depth, based on useage and availability, for young Atlantic salmon in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

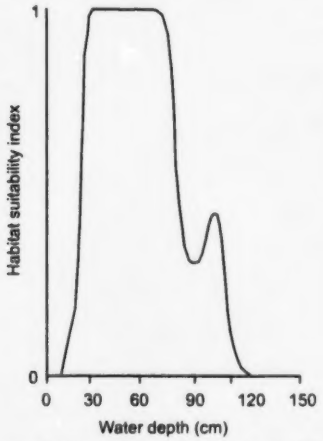
Heggenes *et al.* 1994



Salmon parr Habitat Suitability Index for depth. This curve applies to large rivers.

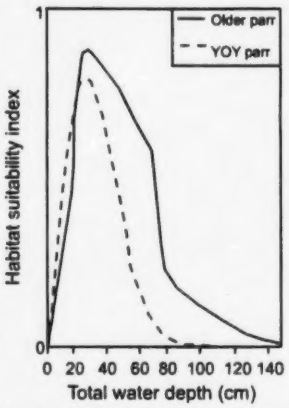
Boudreau *et al.* 1994

Depth suitability criteria for various life stages of Atlantic salmon



Habitat suitability index curves for depth, based on habitat use, for young Atlantic salmon in the R. Gjengedselva; (After Heggenes and Saltveit 1990)

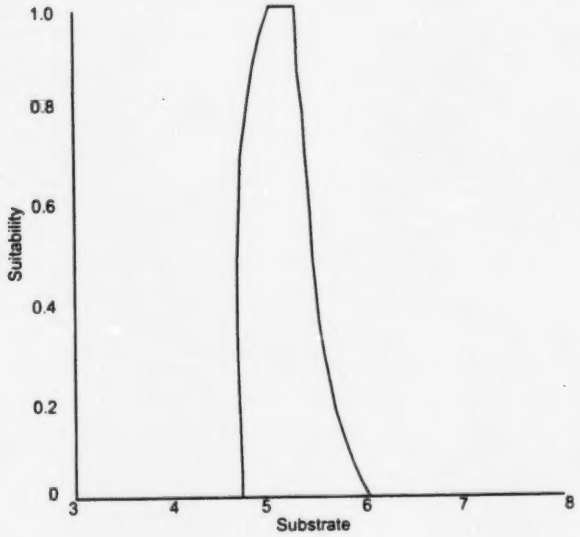
Heggenes *et al.* 1994



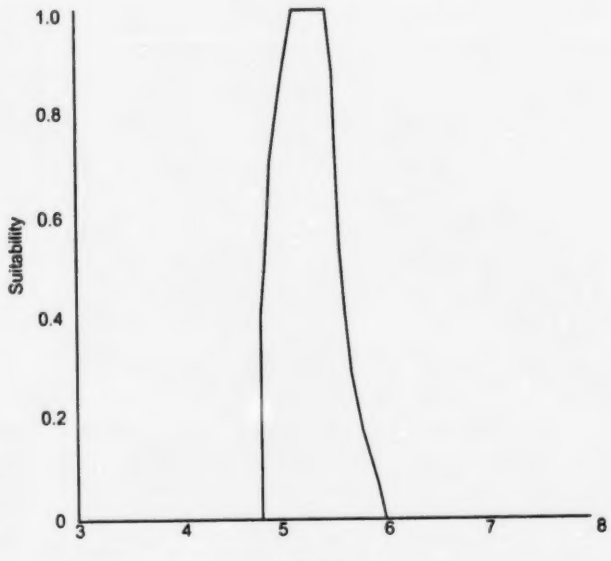
Habitat suitability curve for use of water depth by Atlantic salmon parr in streams. Young-of-the-year use more shallow areas than older parr, which are tolerant to use of different water depths (modified after Heggenes 1991)

Hegennes 1994

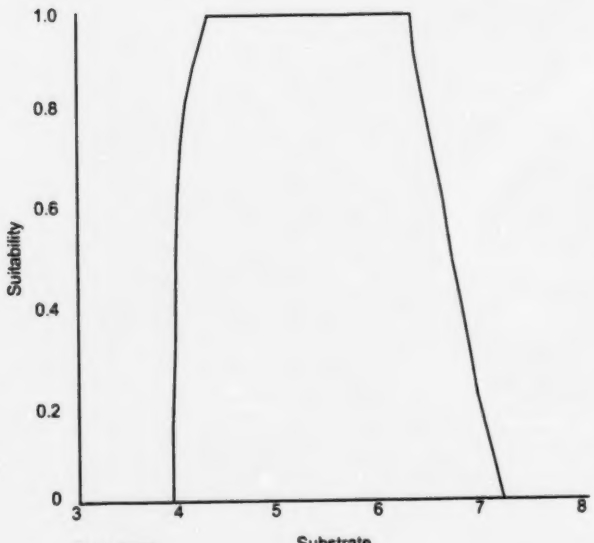
Substrate suitability criteria for various life stages of Atlantic salmon



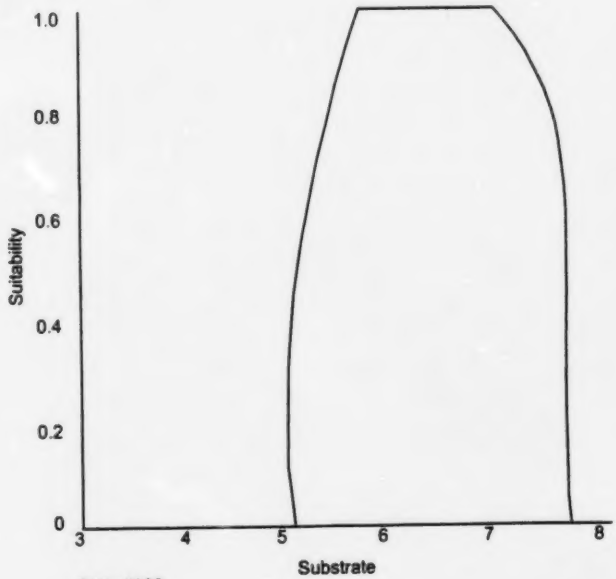
Bietz 1982



Bietz 1982



Bietz 1982

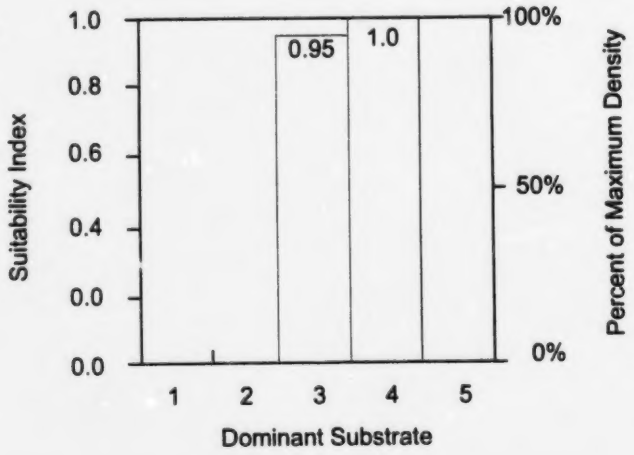


Bietz 1982

Substrate suitability criteria for various life stages of Atlantic salmon

Dominant substrate for spawning and embryo incubation.

Stanley and Trial 1992



Dominant substrate for fry

1 Fines < 0.5 mm

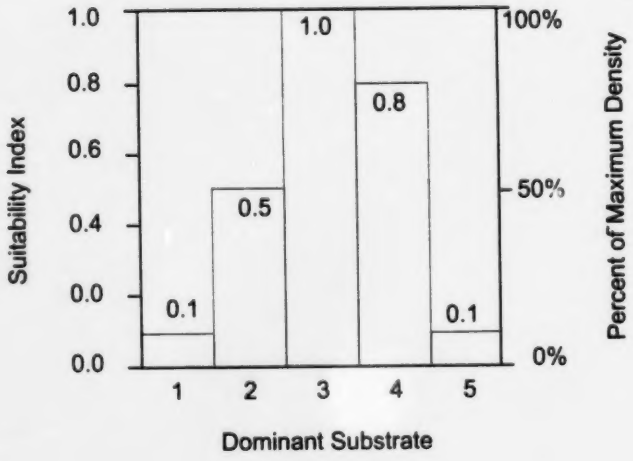
2 Sand 0.5 to 2.2 mm

3 Pebble-gravel 2.2 to 22.2 mm

4 Cobble 22.2 to 256 mm

5 Boulder > 256 mm

Stanley and Trial 1992



Dominant substrate for parr

1 Fines < 0.5 mm

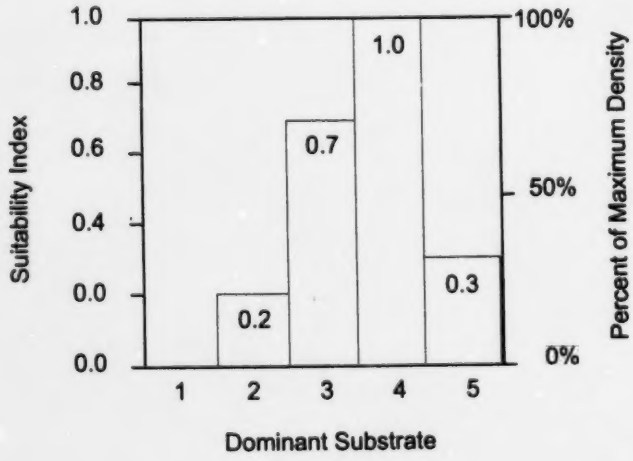
2 Sand 0.5 to 2.2 mm

3 Pebble-gravel 2.2 to 22.2 mm

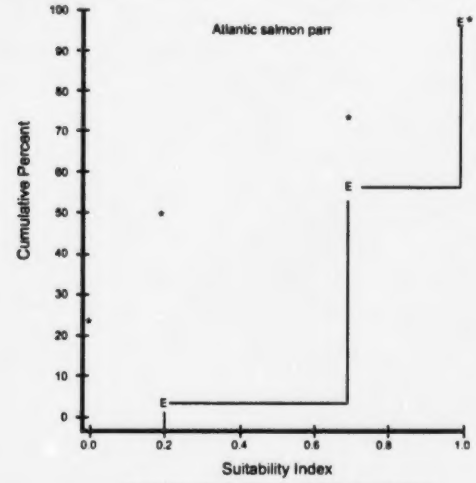
4 Cobble 22.2 to 256 mm

5 Boulder > 256 mm

Stanley and Trial 1992

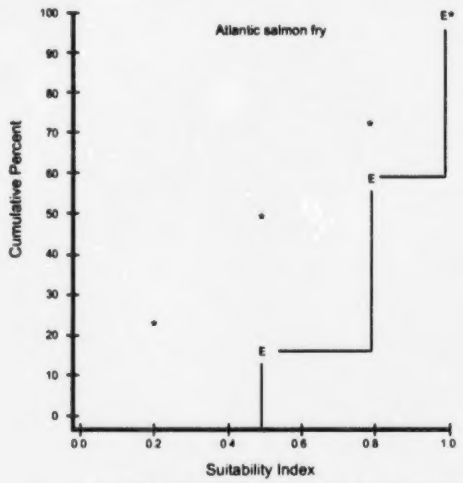


Substrate suitability criteria for various life stages of Atlantic salmon



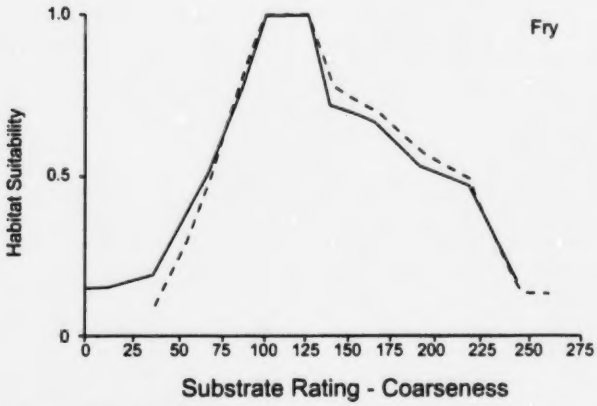
Trial 1989

Cumulative distributions of suitability for substrate used by Atlantic salmon parr in Maine streams (E) and for the points on the substrate suitability curve for parr (*) in Trial and Stanley (1984).

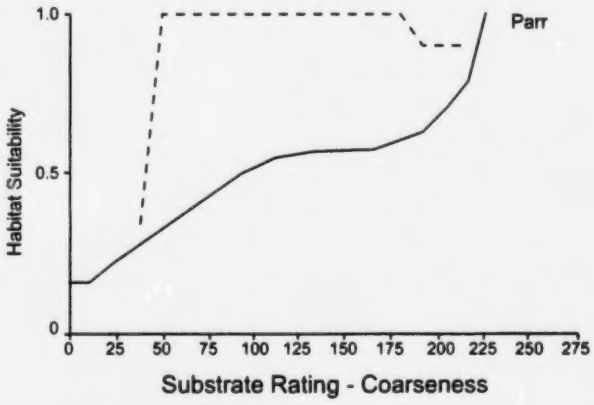


Trial 1989

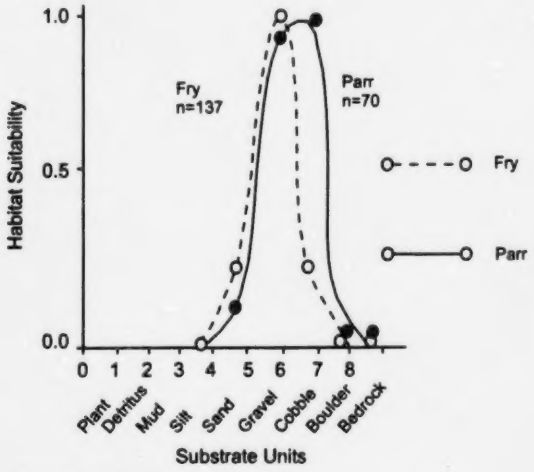
Cumulative percent versus suitability for substrate used by fry in Maine streams (E) and for the points on the suitability curve for parr (*) in Trial and Stanley (1984).



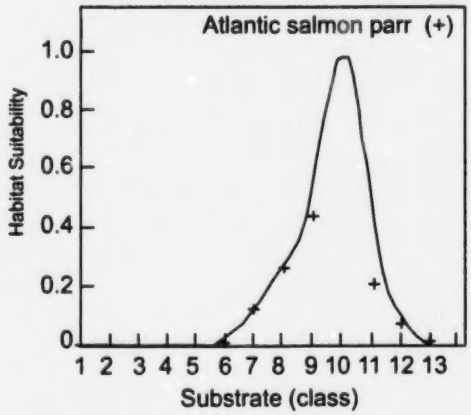
Scruton and Gibson 1993



Scruton and Gibson 1993

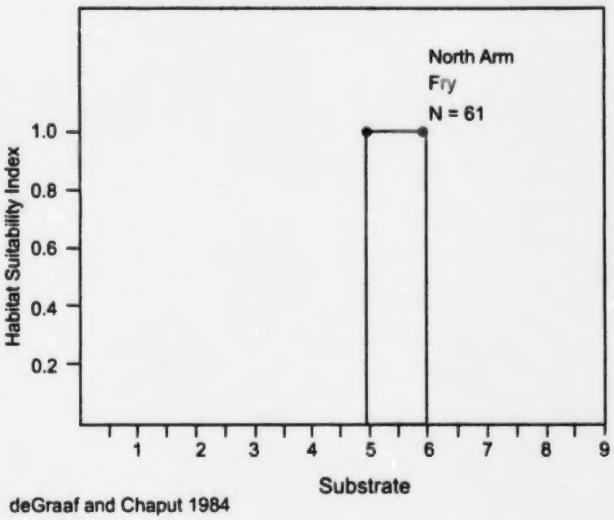


Shirvall and Morantz 1983

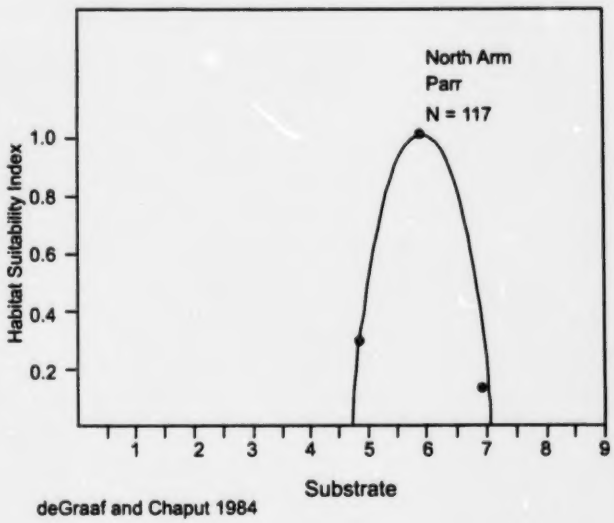


Heggenes and Saltveit 1990

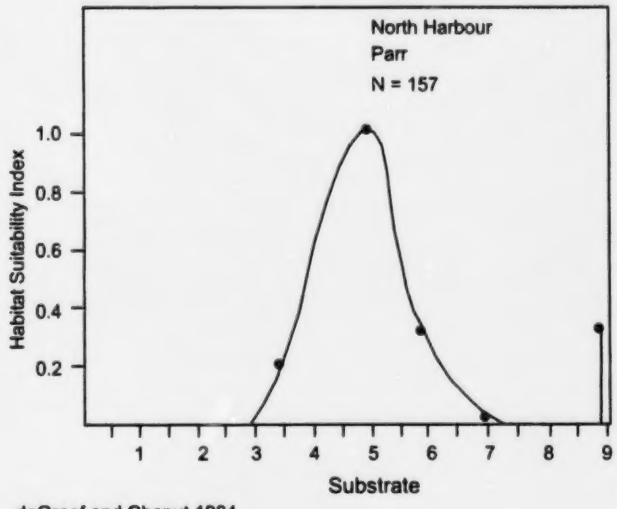
Substrate suitability criteria for various life stages of Atlantic salmon



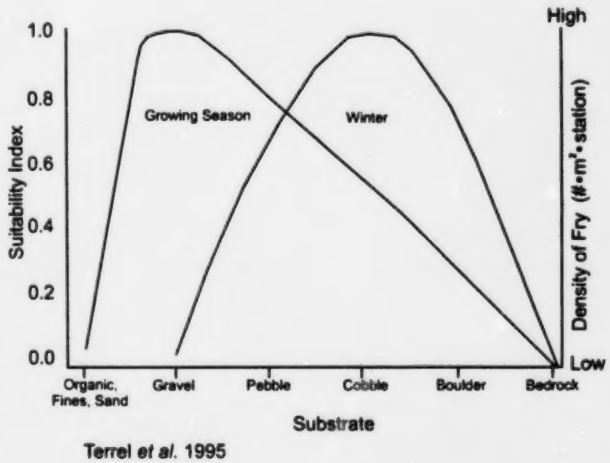
deGraaf and Chaput 1984



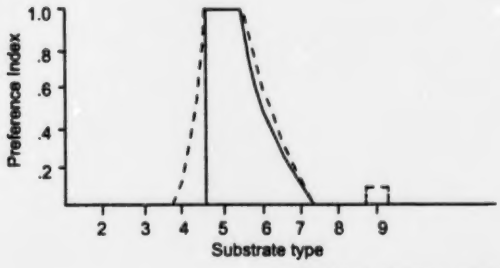
deGraaf and Chaput 1984

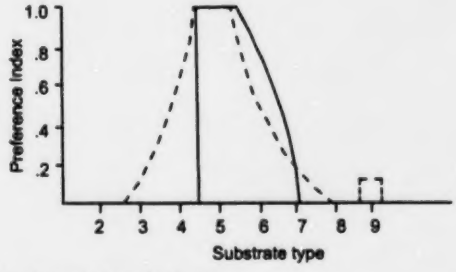


deGraaf and Chaput 1984



Terrel *et al.* 1995

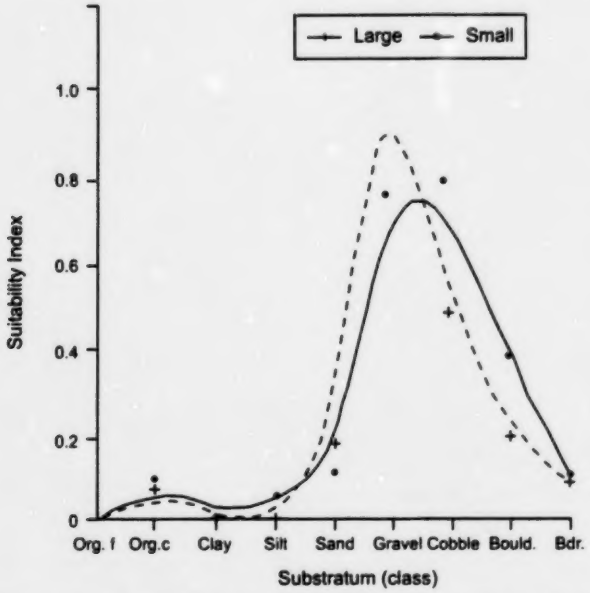




Habitat-preference curves for Atlantic salmon YOY and parr in type-A (North Arm River) and type-B (North Harbour River) habitats in Newfoundland

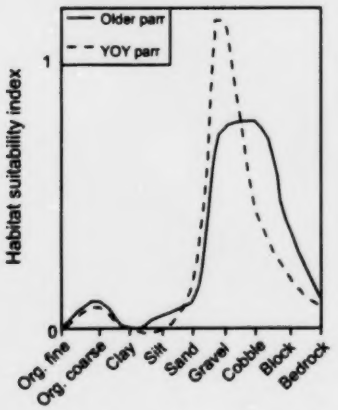
deGraaf and Bain 1986

Substrate suitability criteria for various life stages of Atlantic salmon



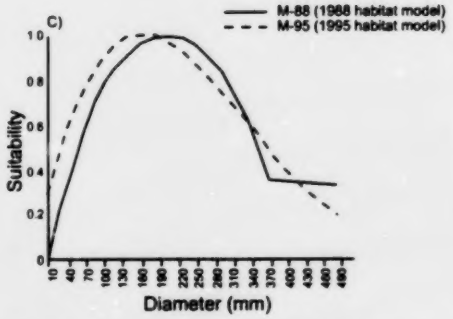
Generalized habitat suitability curve for use of substrate particle size by Atlantic salmon parr (solid line) and young of the year (dotted line), based on several published studies. (Curve calculated by the author). Org.f. = organic fine materials; Org.c. = organic coarse material; Clay = < 0.004 mm; Silt = 0.004 - 0.062 mm; Sand = 0.063 - 2.0 mm; Gravel = 2.1 - 64.0 mm; Cobble = 64.1 mm - 250 mm; Bould. = > 250 mm; Bdr. = bedrock

Heggenes 1990



Habitat suitability curve for substrate use by young Atlantic salmon in streams. Young-of-the-year favour use of gravel and cobble while older parr also use coarser substrates (modified after Heggenes 1990)

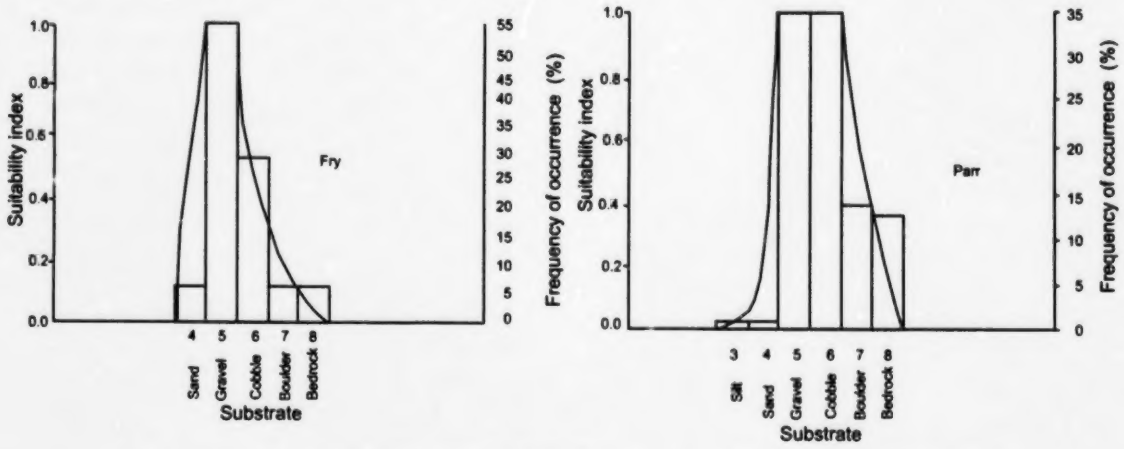
Heggenes 1994



Salmon parr Habitat Suitability Index substrate mean size. This curve applies to large rivers.

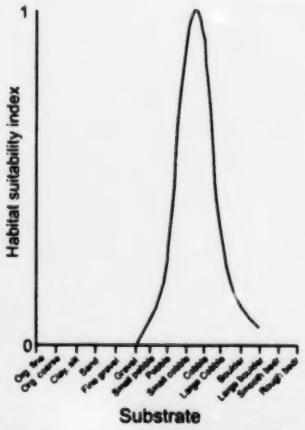
Boudreau *et al.* 1994

Substrate suitability criteria for various life stages of Atlantic salmon



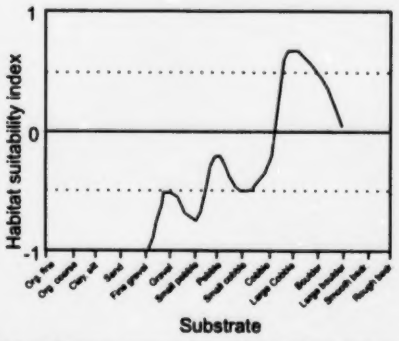
Substrate selection by Atlantic salmon fry and parr in six Nova Scotia and New Brunswick rivers in 1982-1984. Bars represent frequency of occurrence; curves indicate the suitability index.

Morantz *et al.* 1987



Habitat suitability index curves, based on habitat use, for young Atlantic salmon in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



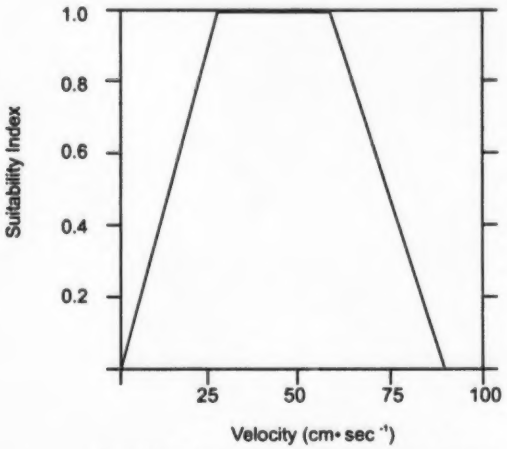
Habitat preference curves, based on useage and availability, for young Atlantic salmon (solid line) and brown trout (darted line) in the R. Gjengedselva; a) mean water velocity; b) depth; c) substrate. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994

Appendix F

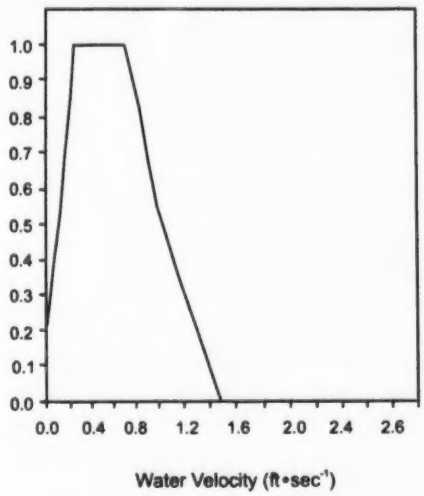
Microhabitat suitability criteria for various life stages of brook trout

Velocity suitability criteria for various life stages of brook trout



Average velocity (cm per second) over spawning areas, during embryo development.

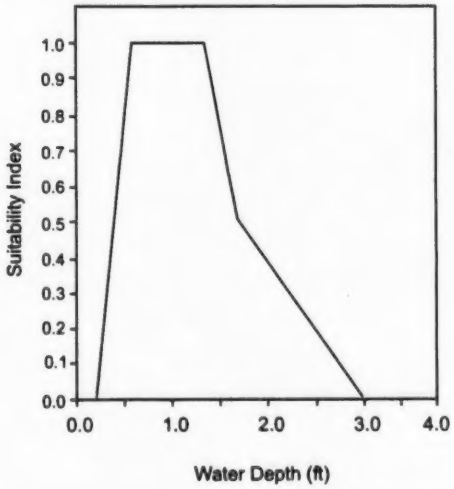
Raleigh 1982



Water velocity SI curve for juvenile brook trout developed using the Delphi method

Jirka and Homa 1990

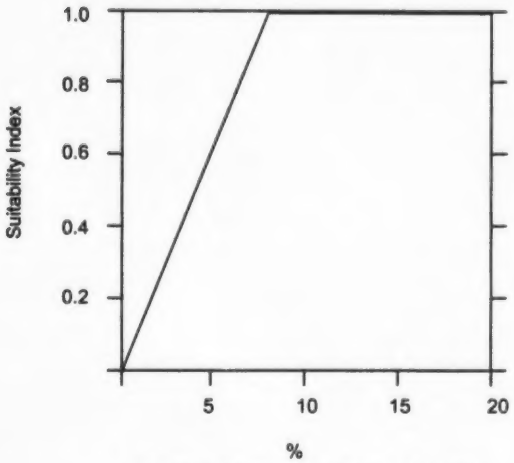
Depth suitability criteria for various life stages of brook trout



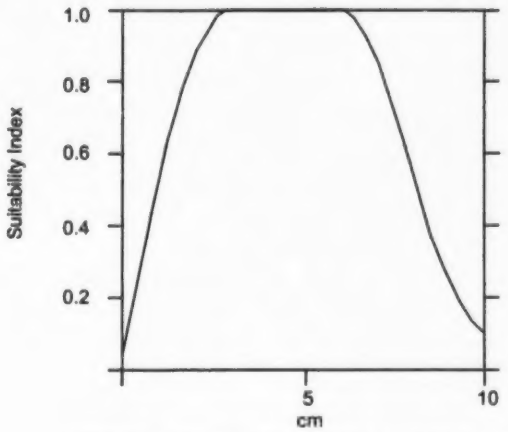
Water depth SI curve for juvenile brook trout developed using the Delphi Method

Jirka and Homa 1990

Substrate suitability criteria for various life stages of brook trout

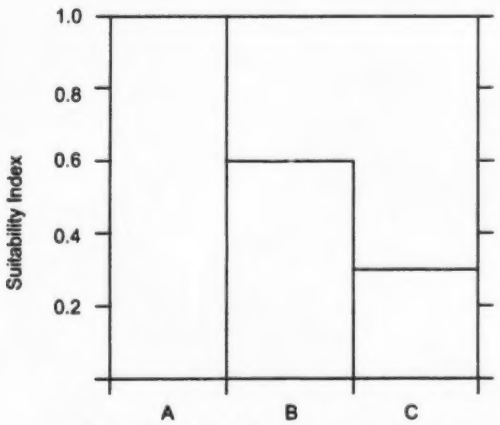


Percent substrate size class (10-40 cm) used for winter and escape cover by fry and small juveniles.
Raleigh 1982



Average size of substrate between 0.3 - 8 cm diameter in spawning areas, preferably during the spawning period

Raleigh 1982



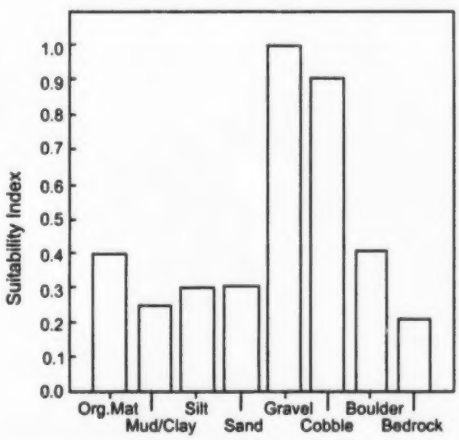
Dominant (≥ 50%) substrate type in riffle-run areas for food production

A) Rubble or small boulders or aquatic vegetation in spring areas dominant, with limited amounts of gravel, large boulders, or bedrock.

B) Rubble, gravel, boulders and fines occur in approximately equal amounts or gravel is dominant. Aquatic vegetation may or may not be present.

C) Fines, bedrock, or large boulders are dominant. Rubble and gravel are insignificant (≤ 25%)

Raleigh 1982



Substrate SI curve for juvenile brook trout developed using the Delphi method

Jirka and Homa 1990

Appendix G

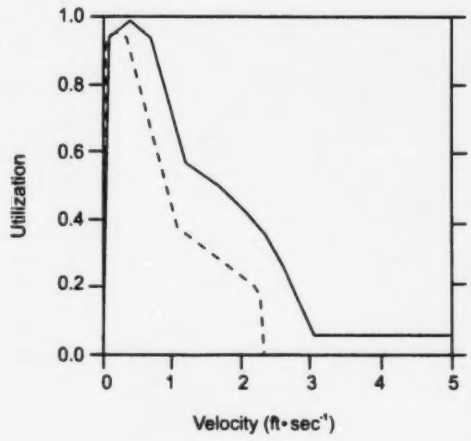
Microhabitat suitability criteria for various life stages of brown trout

Velocity suitability criteria for various life stages of brown trout

—— Mean column velocity

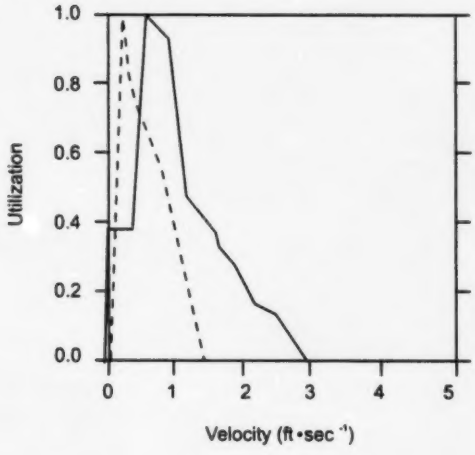
- - - Fish nose velocity
Adults (> 9.4 inches length)
n=352
All activities

Raleigh *et al.* 1986



—— Mean column velocity
- - - - Fish nose velocity
Young-of-year (< 5.5 inches length)
n=210
All activities

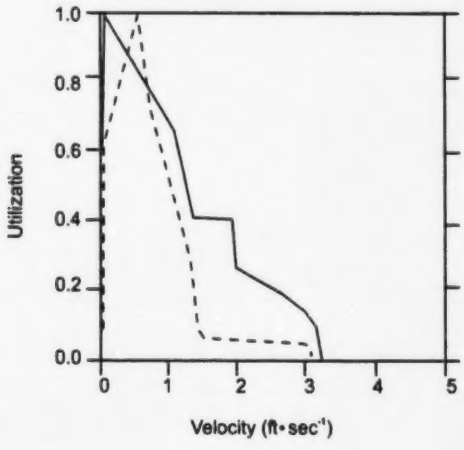
Raleigh *et al.* 1986



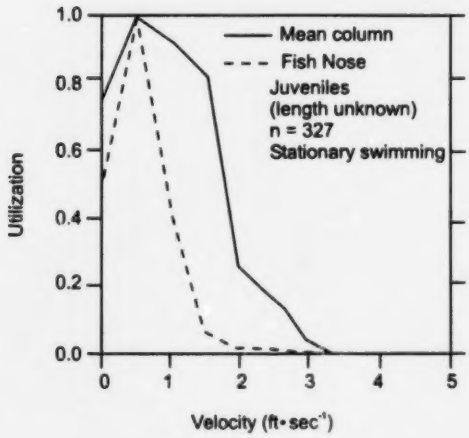
—— Mean column
- - - Fish Nose

Juveniles (5.9 to 9.1 inches length)
n = 239
All activities

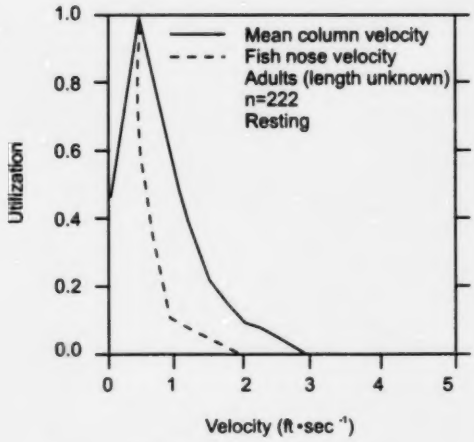
Raleigh *et al.* 1986



Velocity suitability criteria for various life stages of brown trout



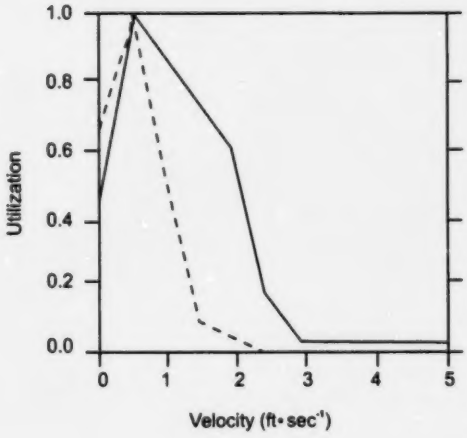
Raleigh *et al.* 1986



Raleigh *et al.* 1986

Mean column velocity

Fish nose velocity
Adults (length unknown)
n=225
Stationary swimming

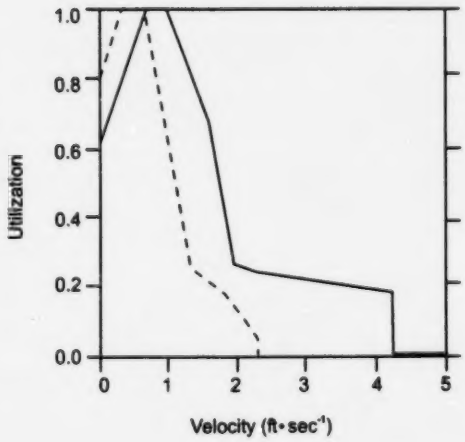


Raleigh *et al.* 1986

Mean column

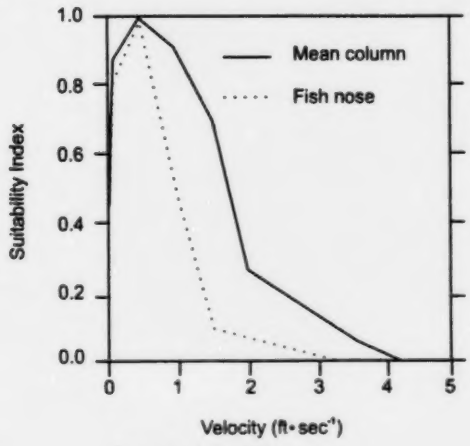
Fish Nose

Juveniles (2.0 to 4.7 inches length)
n = 194
All activities

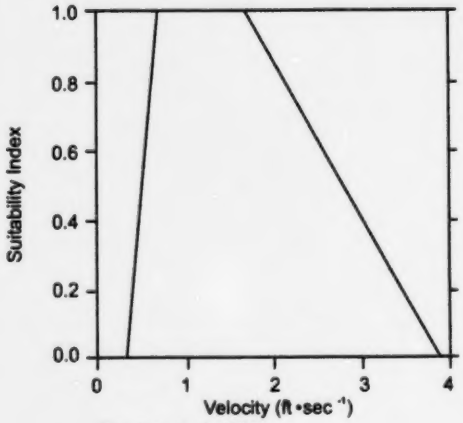


Raleigh *et al.* 1986

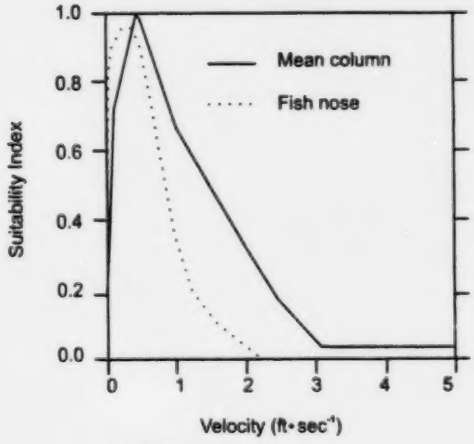
Velocity suitability criteria for various life stages of brown trout



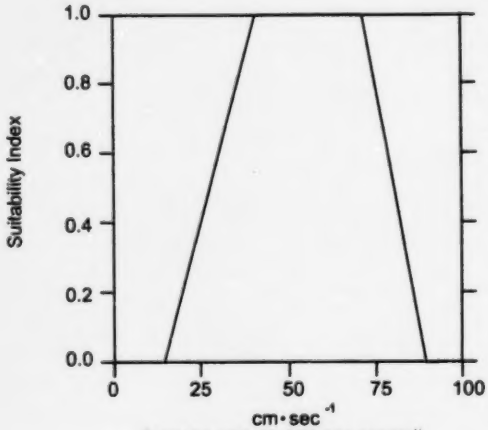
Raleigh *et al.* 1986



Raleigh *et al.* 1986

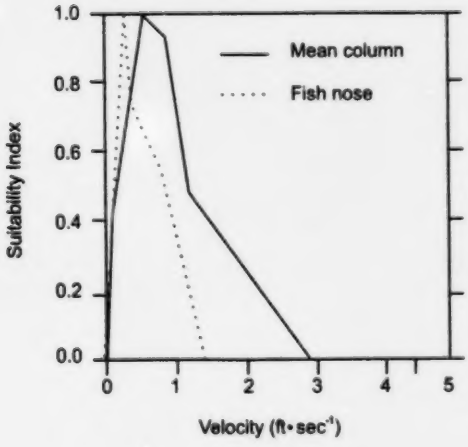


Raleigh et al. 1986

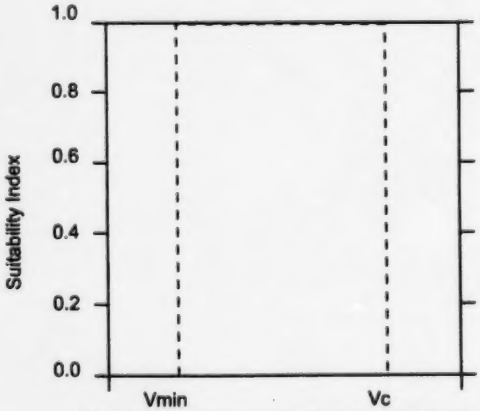


Average velocity (cm per second) over spawning areas during spawning and embryo development.

Raleigh *et al.* 1986



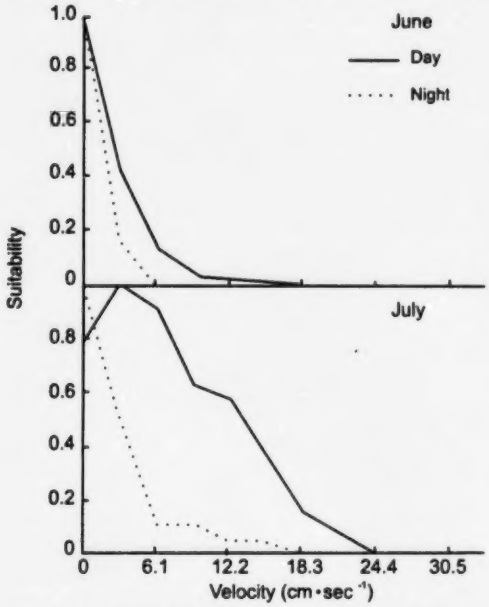
Raleigh *et al.* 1986



Vmin is the minimum velocity necessary to prevent siltation of spawning sites; Vc is the critical velocity, above which scouring of spawning sites will occur.

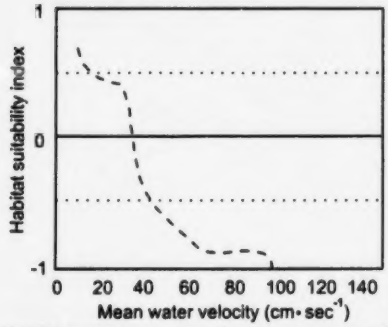
Raleigh *et al.* 1986

Velocity suitability criteria for various life stages of brown trout in Newfoundland



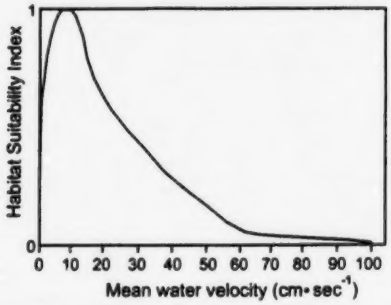
Water velocity suitability curves for young-of-year brown trout for June and July in Douglas Creek, Wyoming.

Harris *et al.* 1992



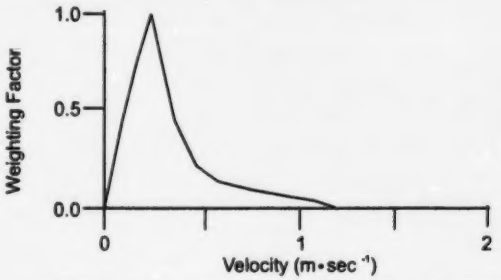
Habitat preference curves, based on usage and availability, for young brown trout in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



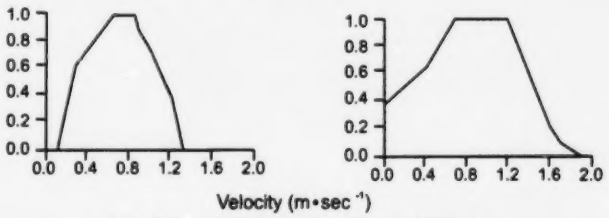
Habitat suitability index curve for use of mean water velocities by brown trout. Trout appear to avoid stillwater and high water velocities (modified after Heggenes 1994).

Heggenes 1994



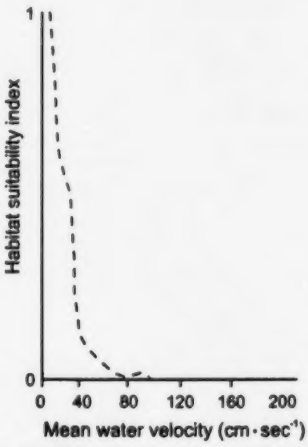
Habitat-suitability weighting curves in relation to water velocity, for brown trout (> 55 mm FL, n = 183) in Rakaia River.

Glova and Duncan 1985



Suitability curves for food producing habitat (Waters 1976)and adult brown trout drift feeding habitat (J. Hayes, Ministry of Agriculture and Fisheries, personal communication)

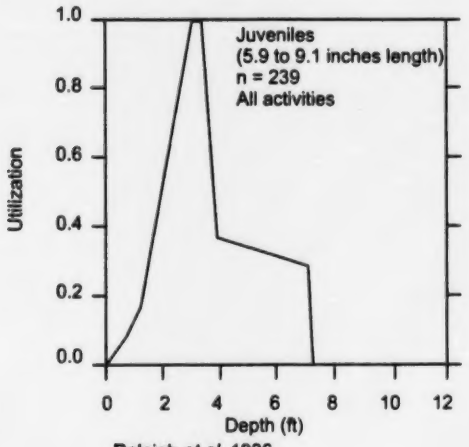
From Jowett 1992



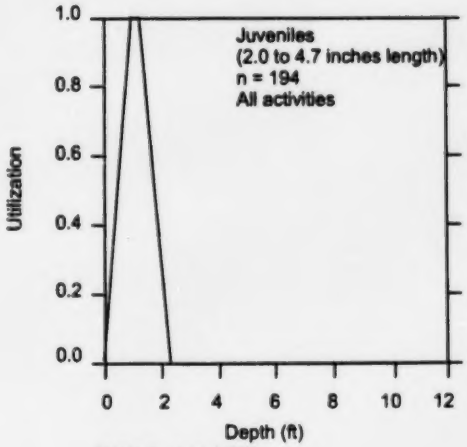
Habitat suitability index curve for velocity, based on habitat use, for young brown trout in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994

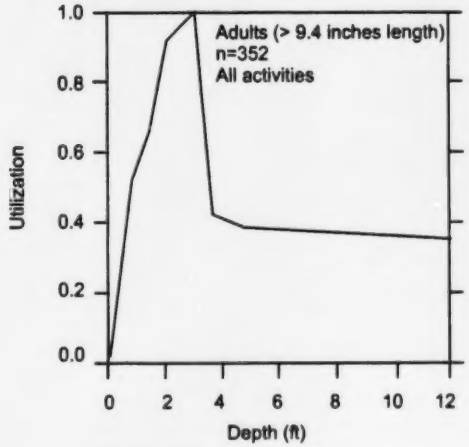
Depth suitability criteria for various life stages of brown trout



Raleigh *et al.* 1986

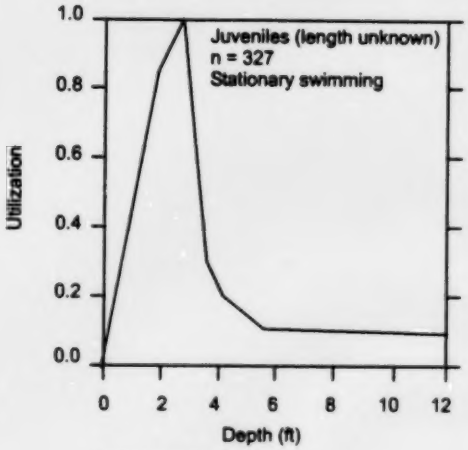


Raleigh *et al.* 1986

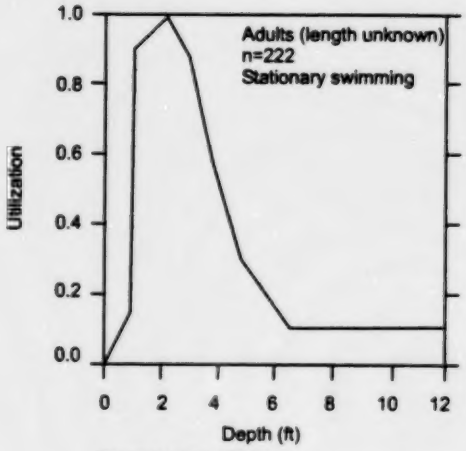


Raleigh et al. 1986

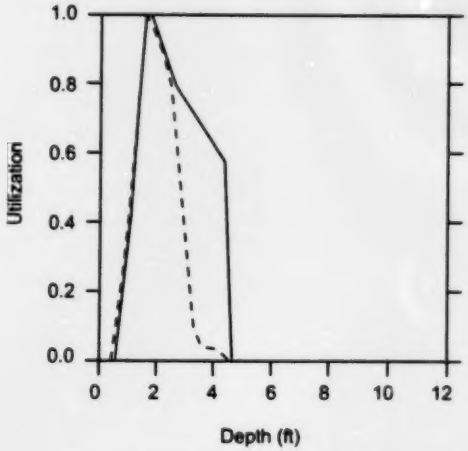
Depth suitability criteria for various life stages of brown trout



Raleigh *et al.* 1986



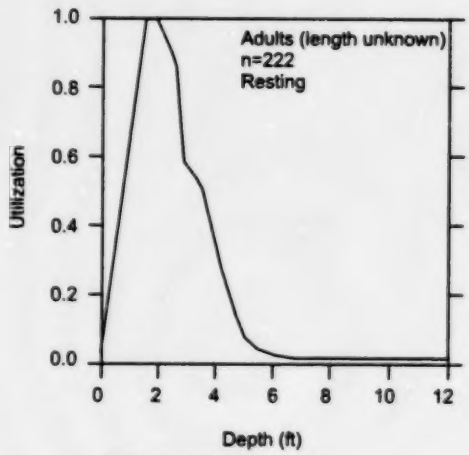
Raleigh et al. 1986



——— Young-of-the-year (< 5.5 inches length)
n=210
All activities

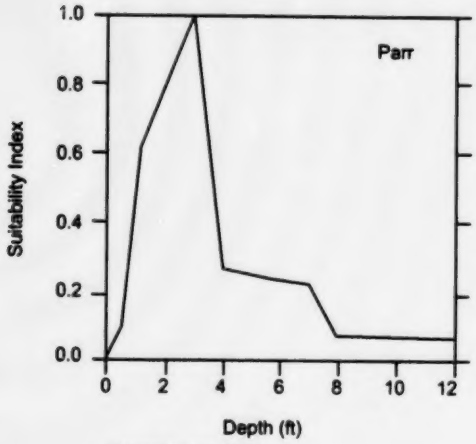
- - - - Age 0
Stationary swimming
n=274

Raleigh *et al.* 1986

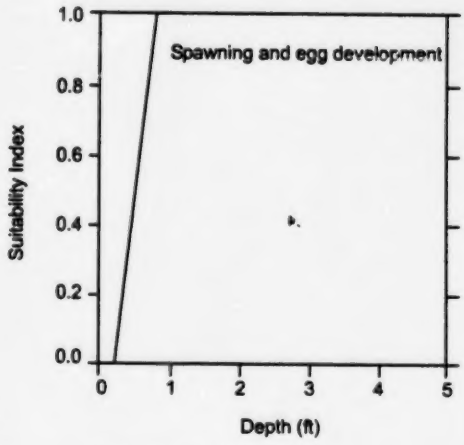


Raleigh *et al.* 1986

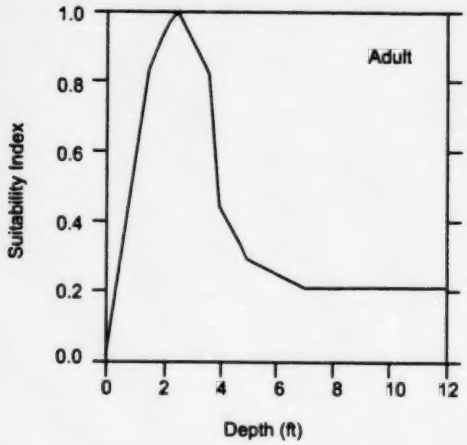
Depth suitability criteria for various life stages of brown trout



Raleigh *et al.* 1986

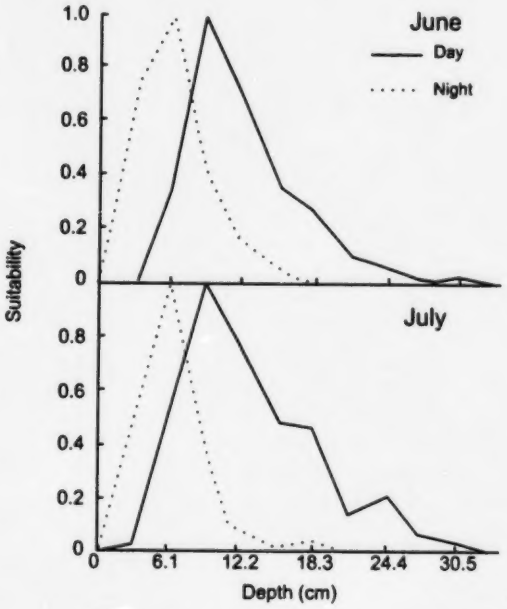


Raleigh et al. 1986



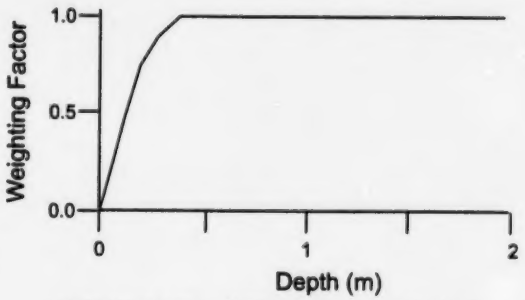
Raleigh et al. 1986

Depth suitability criteria for various life stages of brown trout



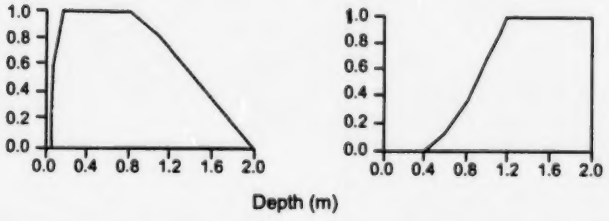
Water depth suitability curves for young-of-year brown trout for June and July in Douglas Creek, Wyoming.

Harris *et al.* 1992



Habitat-suitability weighting curves in relation to water depth, for brown trout (> 55 mm FL, n = 183) in Rakaia River.

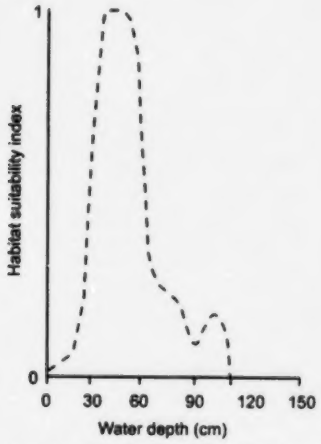
Glova and Duncan 1985



Suitability curves for food producing habitat (Waters 1976) and adult brown trout drift feeding habitat (J. Hayes, Ministry of Agriculture and Fisheries, personal communication)

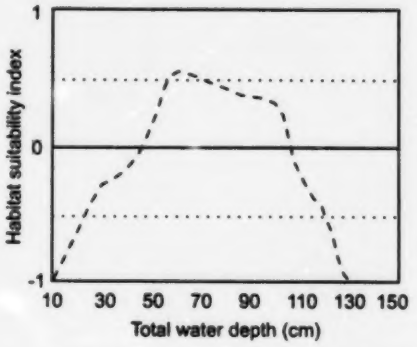
From Jowett 1992

Overhanging cover suitability criteria for various life stages of brown trout



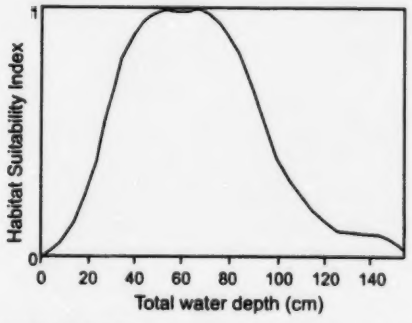
Habitat suitability index curve for depth, based on habitat use, for young brown trout in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



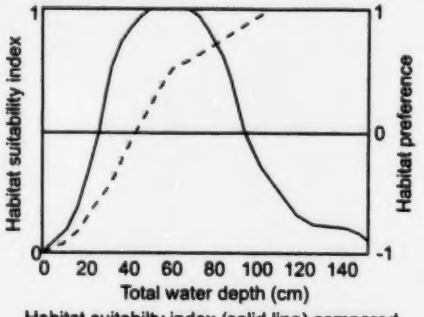
Habitat preference curve for depth, based on useage and availability,for young brown trout in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



Habitat suitability index curve for total water depth use by brown trout in small streams in summer. Trout appear to favour intermediate depths (modified after Heggenes 1994).

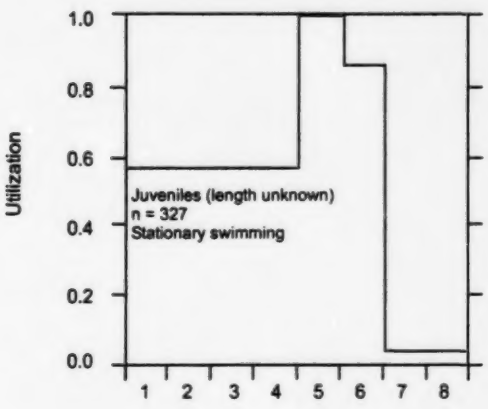
Heggenes 1994



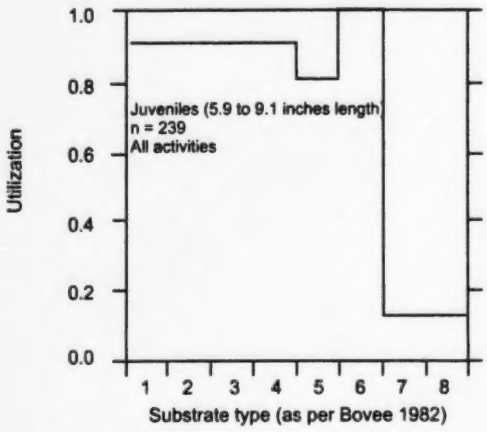
Habitat suitabilty index (solid line) compared to preferences (darted line) for total water depth by brown trout in small streams in summer. Trout strongly prefer the deepest stream areas (modified after Heggenes 1994)

Heggenes 1994

Substrate suitability criteria for various life stages of brown trout

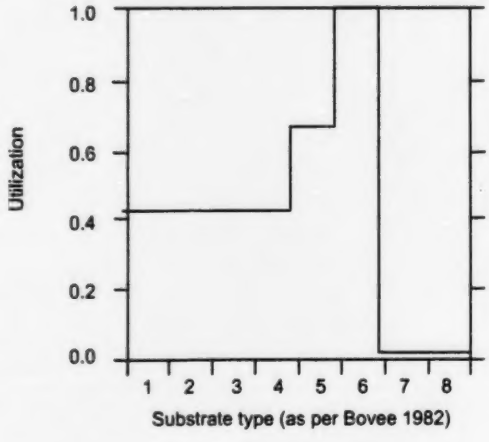


Raleigh *et al.* 1986



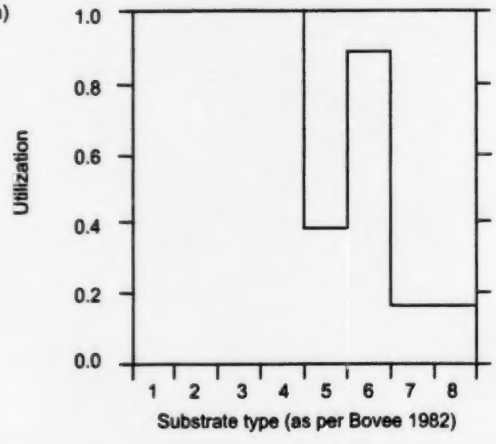
Raleigh *et al.* 1986

Adults (length unknown)
n=222
Stationary swimming



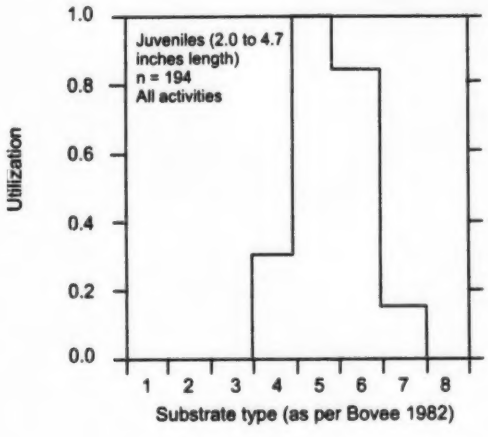
Raleigh *et al.* 1986

Adults (> 9.4 inches length)
n=352
All activities



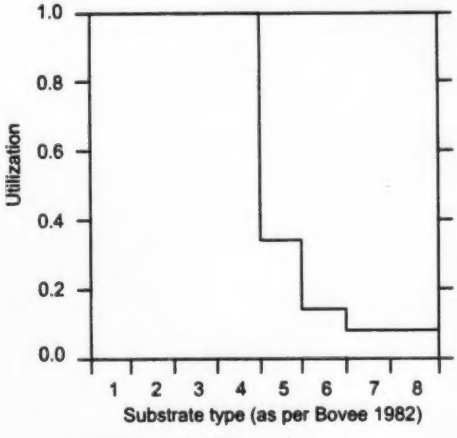
Raleigh *et al.* 1986

Substrate suitability criteria for various life stages of brown trout



Raleigh *et al.* 1986

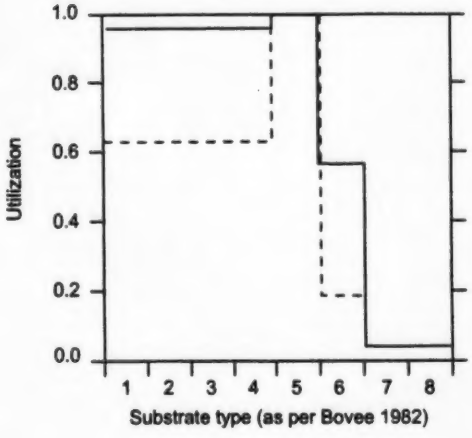
Adults (length unknown)
n=222
Resting



Raleigh *et al.* 1986

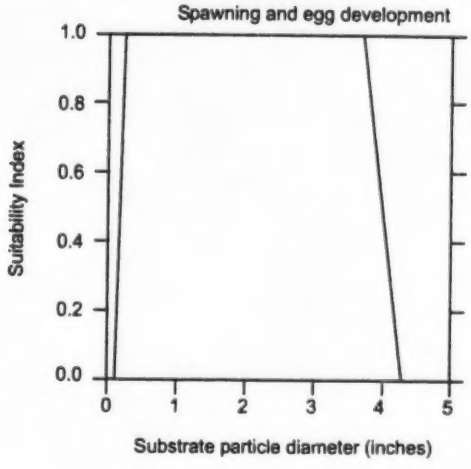
Young-of-year (< 5.5 inches length)
n=210
All activities

Age 0
Stationary swimming
n=274

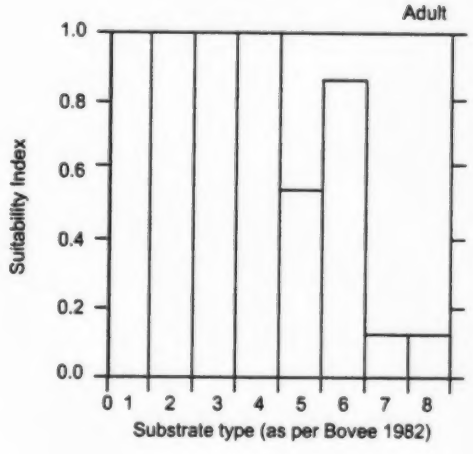


Raleigh *et al.* 1986

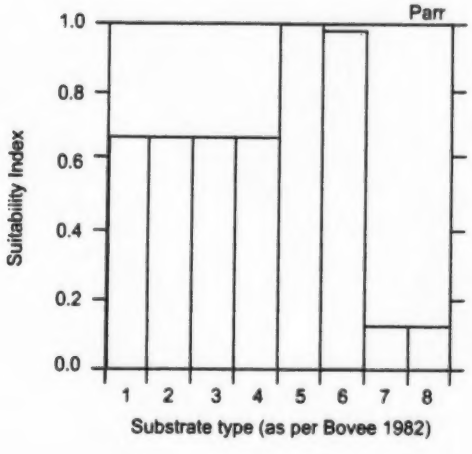
Substrate suitability criteria for various life stages of brown trout



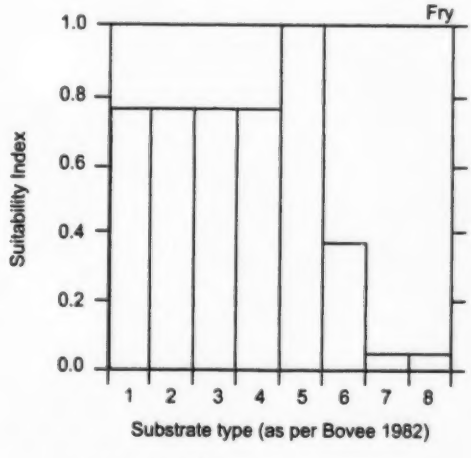
Raleigh *et al.* 1986



Raleigh *et al.* 1986

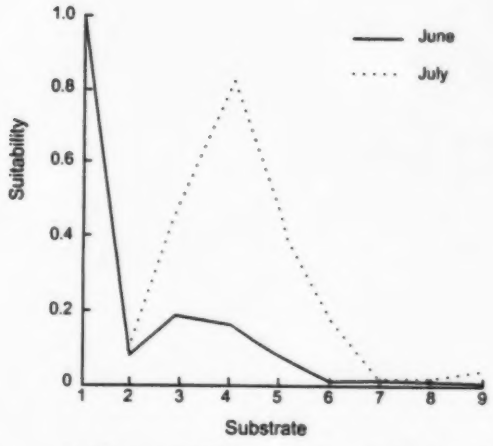


Raleigh *et al.* 1986



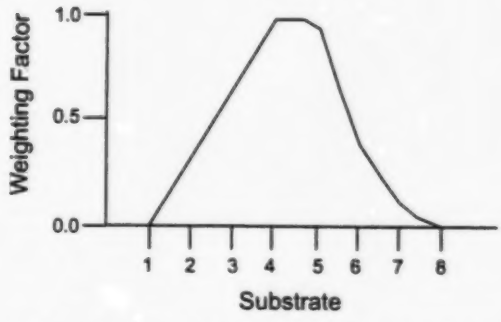
Raleigh *et al.* 1986

Substrate suitability criteria for various life stages of brown trout



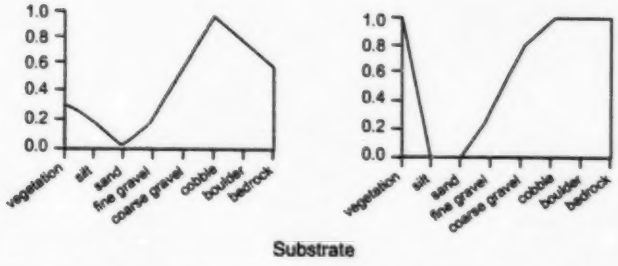
Substrate suitability curves for young-of-year brown trout for June and July in Douglas Creek, Wyoming. Substrate codes are 1 = fines (< 0.5 cm diameter), 2 = small gravel (0.5-2 cm), 3 = medium gravel (3-5 cm), 4 = large gravel; (6-7 cm), 5 = small cobble (8-15 cm), 6 = medium cobble (16-23 cm), 7 = large cobble (24-30 cm), 8 = small boulder (31-58 cm), and 9 = large boulder (> 58 cm).

Harris *et al.* 1992



Habitat-suitability weighting curves in relation to substrate type for brown trout (> 55 mm FL, N = 183) in Rakaia River. Substrate codes; 1, mud; 2, silt; 3, sand; 4, gravel; 5, small cobbles; 6, large cobbles; 7, boulders; 8, bedrock.

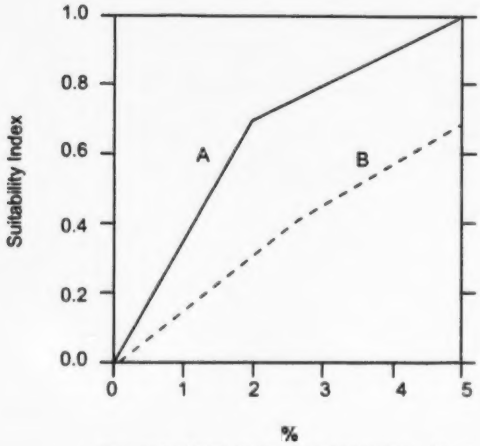
Glova and Duncan 1985



Suitability curves for food producing habitat (Waters 1976) and adult brown trout drift feeding habitat (J. Hayes, Ministry of Agriculture and Fisheries, personal communication)

Jowett 1992

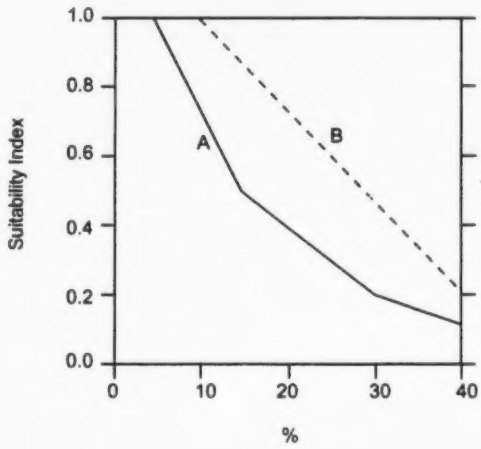
Substrate suitability criteria for various life stages of brown trout



Percent of total study area consisting of two spawning gravel size classes (A and B). Measure gravel sizes of 0.3 to 10 cm in areas ≥ 0.5 m^2 and at depths of ≥15 cm only.

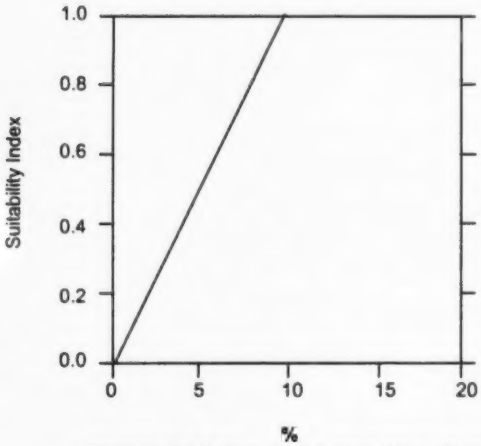
Class A = 1 to 7 cm
Class B = 0.3 to < 1and > 7-10 cm

Raleigh *et al.* 1986



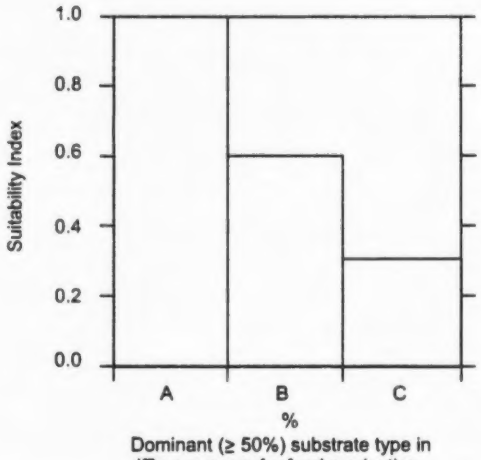
Percent fines (< 3 mm) in riffle-run and spawning areas during average summer flows
A = spawning
B = riffle-run

Raleigh *et al.* 1986



Percent of substrate as size class (10 to 40 cm) used for winter and escape cover by fry and small juveniles.

Raleigh *et al.* 1986



Dominant (≥ 50%) substrate type in riffle-run areas for food production.

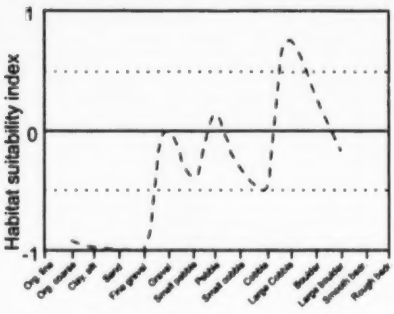
A) Rubble or small boulders, or aquatic vegetation in spring areas, dominant; limited amount of gravel, large boulders, or bedrock.

B) Rubble, gravel boulders, and fines occur in approximately equal amounts or rubble-large gravel mixture are dominant. Aquatic vegetation may or may not be present.

C) Fines, bedrock, small gravel, or large boulders dominant. Rubble and small boulder are insignificant (≥25%).

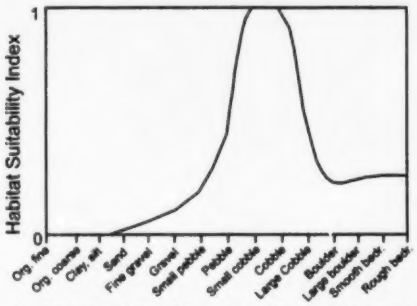
Raleigh *et al.* 1986

Substrate suitability criteria for various life stages of brown trout



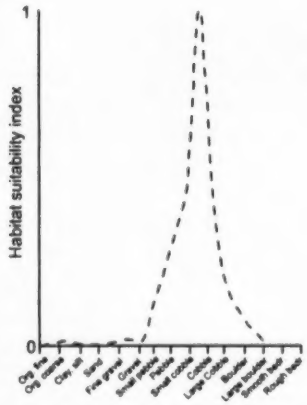
Habitat preference curve for substrate, based on useage and availability, for young brown trout in the R. Gjengedselva. (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994



Habitat suitability index curve for substrate use by brown trout. Trout appear to favour cobble substrate (modified after Heggenes 1994).

Heggenes *et al.* 1994



Habitat suitability index curve for substrate, based on habitat use, for young brown trout in the R. Gjengedselva (After Heggenes and Saltveit 1990)

Heggenes *et al.* 1994

Appendix H

Microhabitat suitability criteria for various life stages of Arctic char

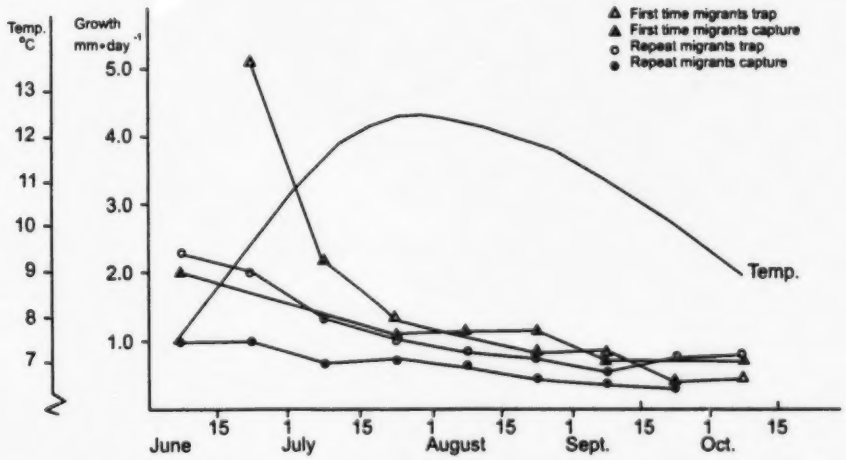
Microhabitat relationships for Arctic charr (Note: This data was not converted into formal Habitat Suitability Indices)

Arctic charr characteristics at three sites on the Koroc River system [1]

Site	n	Mean Water Depth (cm) (SEM)	Mean surface water velocity cm per sec	Mean groundwater pressure head (cm)	Particle diameter range in redd (cm)
A	4	61.75 (21.04)	47.87	+ 1.23	1-6
B	7	80.57 (2.77)	22.22 [2]	+ 0.50	1-15
C	6	123.33 (6.67)	38.50 [3]	nm	1-15

[1] For exact locations of spawning site desiginations see Cunjak *et al.* 1986
[2] Estimates over a 20 m² area where redds were located.
[3] Estimates over a 15 m² area where redds were located.
nm = no hydrological measurements taken;
SEM = standard error of the mean; n = number of redds

Cunjak *et al.* 1986



Mean daily growth in length of Arctic charr captured in the traps when ascending (trap), or captured in the sea (capture), plotted in relation to sea temperature.

Berg and Berg 1989